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AIRCRAFT TECHNOLOGY ASSESSMENT

STATUS OF THE GAS TURBINE PROGRAM

December, 1976

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U.S. ENVIRONMENTAL
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16. Abstracts This report details the advances that have been made in the control of aircraft gas turbine engine emissions. Two technologies of differing complexities have evolved. The success of the first, which controls only hydrocarbons and carbon monoxide, is attributable to innovations in engine operation, the fuel injection system, and the airflow patterns within the combustor. The simplicity of this system gives it wide applicability. The second technology, capable of controlling oxides of nitrogen, in addition to HC and CO, utilizes exotic methods of fuel preparation and multiple zones of combustion. A table, which follows the report, summarizes the EPA technical staff's assessment of the prospects of each engine meeting the levels specified in the 1979 standards, based on manufacturers' data. Control strategies for HC and CO should be ready for implementation by 1979-1980, but, due to the complexity of the oxide of nitrogen control systems, and the fact that requisite levels of technology are currently found only in some of the largest T2 class engines, the practicality of implementation in T1 and APU classes by 1982 is questioned.

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Preface

This is a report which presents an assessment by EPA technical staff of the status of development and application, and of effort made, by aircraft engine manufacturers to comply with the EPA standards applicable to aircraft gas turbine engines. The report is based on analysis of information provided to EPA during public hearings on turbine engine emission control technology held on January 27 and 28, 1976, and on information provided to EPA subsequently through December 1, 1976.

The report is intended to serve as a basis for staff advice to the EPA Administrator on the feasibility of industry compliance with currently promulgated emission standards for subsonic turbine aircraft. Some reviewers of the report may conclude that data in the report are incomplete or obsolete. We solicit from readers of this report any new or additional information bearing on either the accuracy or the completeness of the information presented.

Comments should be sent to the Director, Division of Emission Control Technology, Environmental Protection Agency, 2565 Plymouth Road, Ann Arbor, Michigan, 48105.

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Summary

The principal findings of the EPA aircraft gas turbine technology assessment program, as reported herein, suggest a qualified optimism for the eventual control of a majority of those engines which may be expected to be produced in significant numbers in the future. The major area of difficulty is the group of engines for which even marginally adequate technology has not been identified.

In general, significant technological advances have been made. Two basic technologies of disparate complexity have evolved. The first and relatively simple technology controls only hydrocarbons (HC) and carbon monoxide (CO). This control is achieved through changes in the engine operation, modest changes to the fuel injection system, and modest changes to the airflow pattern within the combustor. Because of the low level of complexity generally found in it, this first technology is easily retrofitable in most applications.

The second and considerably more complex technology is capable of significant control of the oxides of nitrogen (NOx) and when used in conjunction with techniques of the first technology general control of all three pollutants is realized. This control of NOx is achieved through exotic methods of fuel preparation (e.g., premix/prevaporization) and multiple zones of combustion (e.g., staging). Combustion systems and the auxiliary fuel controls which incorporate these concepts are radically different from existing conventional systems and consequently, such new systems do not lend themselves readily to retrofit. Also, the greater complexity of this technology necessitates longer periods for both development and proving.

The following table summarizes the EPA technical staff's assessment of the prospects of each engine meeting the levels specified in the 1979 standards, based on the data available to the EPA as of December 1, 1976. The table is divided into two segments, one for compliance with the hydrocarbon and carbon monoxide standards and the other for compliance with the oxides of nitrogen standard. The overriding limitation of the validity of this table is the accuracy and completeness of the data which has been supplied to the EPA by the manufacturers. Some manufacturers have supplied relatively voluminous data; others very little. Further, data that are presented may occasionally be limited only to the more conservative or to that which tends to be favorable to the industry position; the true potential of a low emissions concept may not be given proper credit here as a result. Consequently, industry may well have progressed further than is indicated in this summary.

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Industry Status

	HC and CO prospects**				NOx prospects**				
Engine	**1979**	**1980**	**1981**	**later**	**1980**	**1981**	**1982**	**1983**	**later**
T1 Class (small jet engines)									
1. AiResearch									
TFE731	good						good		
ATF3	unknown				unknown				
2. Pratt & Whitney of Canada									
JT15D		fair					fair		
3. Avco-Lycoming									
ALF502	fair						good		
4. General Electric									
CJ610	poor----------	----------	----------	----------	already met				
CF700	poor----------	----------	----------	----------	already met				
5. Pratt and Whitney									
JT12A	poor----------	----------	----------	----------	already met				
6. Rolls Royce									
M45H		good			good				
RB401	good				good(1979)				
T2, T3, T4 Classes (large jet engines)									
1. Pratt and Whitney									
JT9D-7		good					good		
JT9D-70		good							good
JT10D	good at certification date				good at certification date				
JT3D	poor----------	----------	----------	----------	poor----------	----------	----------	----------	----------
JT8D		fair			poor----------	----------	----------	----------	----------
2. General Electric									
CF6-6	good				poor----------	----------	*	----------	----------
CF6-50	fair				poor----------	----------	----------	*	----------
CFM56	fair							good	
3. Rolls Royce									
RB211-22B		fair			good (date unknown)				
RB211-524		good			good (date unknown)				
Spey511	poor----------	----------	----------	----------	unknown				
Spey555	poor----------	----------	----------	----------	unknown				
P2 Class (turboprop engines)									
1. AiResearch									
TPE331	good				already met				
2. Pratt and Whitney of Canada									
PT6A-27		good			already met				
PT6A-41		good			already met				
3. Avco-Lycoming									
LTP101	fair	good			good (1979)				
T5321A	already met				already met				
PLT27	already met				already met				
4. Allison									
250		good			already met				
501			good		already met				
5. Rolls Royce									
Dart		fair			good				
Tyne	unknown				unknown				
APU Class (on board power)									
1. AiResearch									
GTCP85	good				poor----------	----------	----------	----------	----------
TSCP700	already met					good			
GTCP36	good				unknown				
GTCP30	already met				unknown				
GTCP660		good			poor----------	----------	----------	----------	----------
2. Pratt & Whitney of Canada									
ST6	already met					good			
3. Solar									
Titan-39	unknown				unknown				

* GE NOx technology available but inadequate for compliance.

** Prospects for meeting the existing levels specified by the EPA 1979 standards for newly manufactured engines by January 1 of the indicated year.

Again, qualified by the small amount of data supplied by the industry at large to EPA, the control of hydrocarbons (HC) and carbon monoxide (CO) appears quite successful in most cases with techniques which can be considered acceptable for retrofit, if necessary. This control can generally be available by 1979-80. It is of course possible that this judgment is conservatively tempered by the nature of the data.

In contrast, control of the oxides of nitrogen (NOx) is far more uncertain. In fact, only among some of the largest T2 (commercial jet) class engines has the requisite technology advanced to the stage of being demonstrated in an engine. For the T1 and APU classes, in particular, the status figures, though optimistic, are based largely upon projections of limited demonstrations. While effective control may be generally available to the T1 and T2 classes by 1982 and to the APU class by 1981, though not always to the level dictated by the standards, (e.g. CF6), there is considerable question as to the practicality of incorporating such mechanisms into T1 and APU class engines. The P2 class generally already complies with its NOx standard. The techniques necessary for effective control of NOx are considerably more complex than that required for only HC and CO control and consequently do not lend themselves as readily to retrofit.

Section I. Foreword

On July 17, 1973 regulations controlling the gaseous and smoke emissions from aircraft engines were promulgated (reference 66). Except for the fuel venting requirement and a few specific cases of smoke standards, these regulations are scheduled to go into effect in 1979 for all newly manufactured gas turbine engines (turbojets, turbofans, turboprops, and auxiliary power units), in 1980 for newly manufactured, non-radial type piston engines, and in 1981 for newly certified (i.e., newly designed) turbojets or fans. The interval between the promulgation date and the compliance dates is intended to permit the development of the necessary technology as required by the Clean Air Act (1970).

The purpose of this report is to summarize the status of the development of low emissions technology for aircraft gas turbines. The basic issues of the investigation are:

(1) What is the available technology; what are the concepts involved and how effective are they in reducing aircraft gas turbine emissions?

(2) What efforts have the manufacturers made and with what success in their attempts to comply with the standards and what more could be done, if necessary, in a timely manner?

(3) How much time is necessary to fully incorporate a certain technology into production?

These issues are treated from both a general perspective (Section III) and a specific or engine-by-engine perspective (Section V).

This report attempts to address the questions through various analyses. The major qualification of these analyses is the uncertainty of the completeness and accuracy of the data which has been supplied to the EPA by the manufacturers. Some manufacturers have supplied relatively voluminous data; others, very little. Further, data that are presented may occasionally be limited only to the more conservative or to that which tends to be favorable to the industry position; the true potential of a low emissions concept may not be given proper credit here as a result.

Section II. Introduction

Section 231 of the Clean Air Act, as amended by Public Law 91-604, directs the Administrator of the Environmental Protection Agency to:

(1) investigate emissions of air pollutants from aircraft to determine the extent to which such emissions affect air quality and to determine the technological feasibility of control, and

(2) establish regulations for the control of emissions from aircraft or aircraft engines if such control appears warranted in the light of the investigation referred to above.

Furthermore, the Clean Air Act states that any such regulations can take effect only after sufficient time has been allowed to permit the development and application of the requisite technology.

The EPA has complied with both mandates of the Clean Air Act, first, by publishing a report, "Aircraft Emissions: Impact on Air Quality and Feasibility of Control," (reference 90) which concluded that the impact on air quality by aircraft was sufficient to justify control and that such control was technologically feasible, second, by publishing a report, "Assessment of Aircraft Emission Control Technology" (reference 26), which offered the best projection at that time of the feasibility of control with the knowledge then available, and third, by promulgating standards limiting the emissions from aircraft engines (reference 66).

In keeping with the spirit of the instructions to determine the technological feasibility of control and to allow sufficient time to permit the development and application of the technology, the EPA has established an Aircraft Technology Assessment Program for the purpose of monitoring the many programs for the development of the low emissions technology for aircraft engines, both piston and gas turbine. This program for gas turbines was begun in July 1974.

Through the cooperation of the industry and the several government agencies working in this area, the EPA received in the past two years information from which it has attempted to assess the status of the development of aircraft engines having low emissions. In addition, the recent hearing in Washington, January 27-28, 1976, which was originally intended for response to the Notice of Proposed Rulemaking (NPRM) for the retrofit of large T2 class engines with low emissions combustors (reference 92) was expanded to permit testimony relating to other aspects and issues of the aircraft emissions regulations. This permitted the acquisition of recently generated data from the industry and NASA. Appendix A lists many of the programs which have bearing on the development of low emissions combustors that were brought to EPA's attention. Data from these programs and from the manufacturers' own in-house efforts have been digested and reduced to more manageable proportions while at the same time proper consideration was being given to the many caveats attached. The EPA has been assisted

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in its data gathering and reduction efforts by Arthur D. Little, Inc. Appendix B summarizes the technical data; most of the data points of the figures throughout this report are tabulated therein. Leadtime information was drawn directly from its source which is referenced in the text as presented.

The methodology used in assessing the development status and control potential of low emissions technology is explained in the text as required. In essence the approach taken is to categorize all potential control techniques primarily according to complexity and pollutants controlled. Control effectiveness is then examined in general terms by the degree of complexity. Next, engines are examined individually to discover (1) their best developments, again by the degree of complexity, (2) what might be expected of them if they employed the best control concepts identified in the control effectiveness study, and (3) the leadtimes necessary. The methodology used in the leadtime analysis involves the development of a general hypothetical schedule for each class of engine on which each specific engine is located in accordance with EPA's understanding of its particular situation. This permits a ready determination of the years to go to production for each category of complexity.

This report is a principal product of the EPA technology assessment program and it focuses primarily on the successes and failures of the industry in its attempts to develop the means to comply with the 1979 standards for newly manufactured gas turbine engines. Attention has been given to both the emissions levels that may be achieved with the technologies presently identified and under development, to the leadtimes necessary to incorporate those technologies into engines, and to the problems of application of these technologies. Also, the same attention has been given to the investigation of the proposed retrofit program for in-use engines and its special problems. In addition, the EPA has found it worthwhile here to examine in a preliminary fashion the likelihood of compliance with the later 1981 standards.

Contrary to the anticipation expressed in the introduction to the Interim Report (December 16, 1975), this report does not address the evaluation of piston engine development. Piston engines will be considered in a separate document in the future.

This report specifically considers:

(1) The identification of emissions controlling factors;

(2) The emissions performance of individual control concepts and categories of concepts grouped according to complexity;

(3) The availability and suitability of these control techniques in general and to specific engines;

(4) The best demonstrated performance of each engine within each category of complexity of control technique;

(5) The predicted performance of each engine employing the best recognized applicable control technique in each category of complexity;

(6) The amount of effort put forth by each manufacturer as reflected in the number of and diversity of control techniques investigated or success in reducing emissions;

(7) The development problems and emissions problems of each engine, especially those which appear to be in jeopardy;

(8) The leadtimes necessary to incorporate control techniques of different complexity into production engines;

(9) The potential for compliance with the newly certified engine standards.

The aircraft emission standards (CFR, part 87, described in FR Vol. 38, N. 136, July 17, 1973, p. 19088), for which this report and the aircraft technology assessment program have been undertaken, describe standards for the emission of unburnt hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and visible smoke from aircraft gas turbine engines, newly manufactured and newly certified. The standards for newly manufactured gas turbine engines are presently scheduled to go into effect January 1, 1979, a date selected to allow time for proper development of the requisite technology, while the more stringent standards for newly certified gas turbine engines are scheduled for two years later, January 1, 1981 (as a newly certified engine would allow more latitude to the designer to incorporate additional low emission features, standards for such engines are set commensurately lower). In addition, there are smoke standards applicable to certain in-use engines at earlier dates. The standards are directed at the reduction of aircraft emissions including smoke in the vicinity of major airports which are in or adjacent to major urban areas wherein aircraft emissions will contribute to the general degradation of the air quality.

The standards themselves apply not to the aircraft, but to the engines. The approach to regulate the engines directly instead of the aircraft was taken to minimize the enforcement effort as the same engine is often used in several aircraft applications. Furthermore, all aircraft in which a given engine might be used have generally similar flight profiles and hence have similar emissions signatures in the airport environs.

In accordance with the latitude permitted by the Clean Air Act (1970), EPA found it desirable to establish classes of aircraft and corresponding engine classes to which different sets of standards would apply as determined by the technical, economic, and safety constraints relevant to each class. The classes established are as follows:

Table II-1 Summary of Aircraft Classes

Class	Type	Aircraft Application
P1	Piston engines (excluding radials)	Light general aviation
P2	Turboprop engines	Medium to heavy general aviation; some commercial air transport
T1	Small turbojet/fan engines	General aviation jet aircraft
T2	Large turbojet/fan engines intended for subsonic flight	Commercial subsonic transports
T3, T4	Special classes applying to specific engines for the purpose of instituting early smoke standards	Commercial subsonic transports
T5	Large turbojet/fan engines intended for supersonic flight	SST
APU	Gas turbine auxiliary power units	Many turbojet/turboprop

The emissions levels permitted by the standards are described by an EPA parameter (EPAP) which is defined in the aircraft regulations. Briefly, it is a measure of the total emission of a particular pollutant produced by an engine over a typical landing-takeoff (LTO) cycle normalized with respect to the total power output of the engine over that cycle (units given in Table II-2). As such, larger engines performing greater useful work are permitted proportionally larger amounts of total emissions over smaller engines.

The standards, promulgated in July, 1973 for all classes but T5 and in July, 1976 for that class, are summarized below:

SMOKE STANDARD
CLASS T2 ENGINES

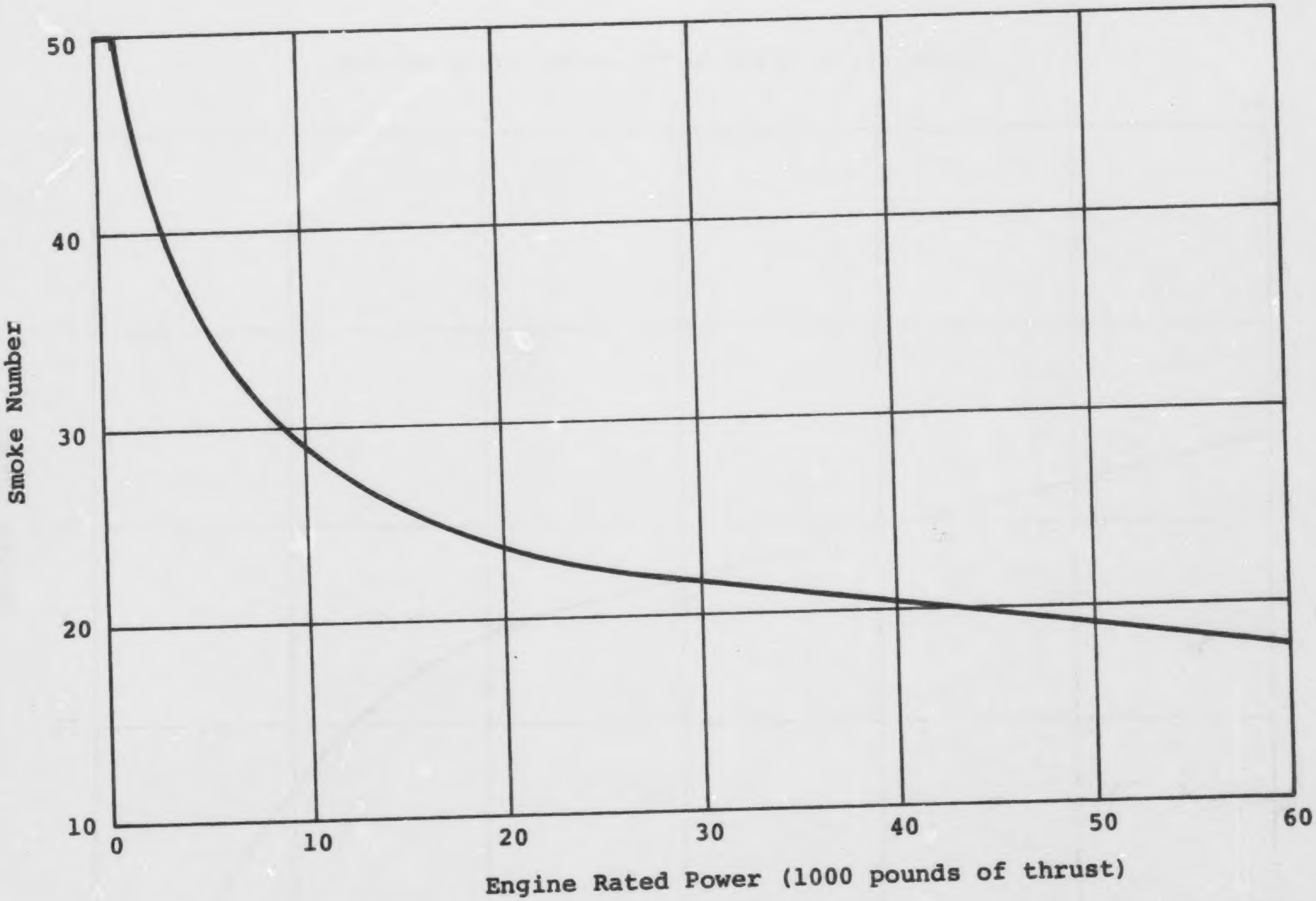

Figure 1

SMOKE STANDARD
CLASS P2 ENGINES

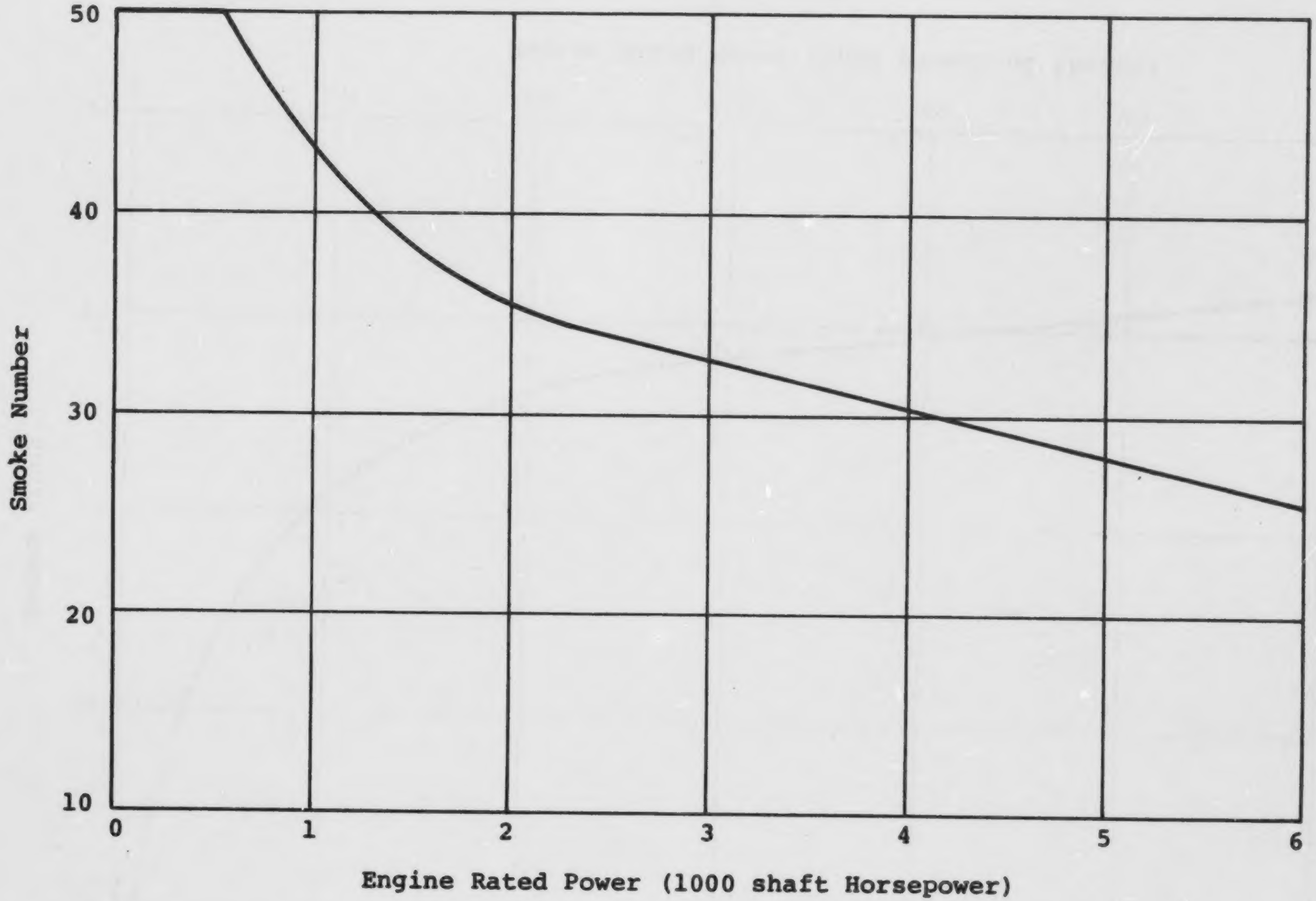

Figure 2

Table II-2

Newly Manufactured Engines

Class	HC	EPAP* CO	NOx	Compliance Date
T1	1.6	9.4	3.7	January 1, 1979
T2	0.8	4.3	3.0	" " "
T3	"	"	"	" " "
T4	"	"	"	" " "
T5	3.9	30.1	9.0	January 1, 1980
P2**	4.9	26.8	12.9	January 1, 1979
APU***	0.4	5.0	3.0	" " "

Smoke is also regulated. For the T1-T5 classes, the acceptable smoke level is given by Figure 1 and for the P2 class by Figure 2. The standards for advanced engines are:

Table II-3

Newly Certified Engines

Class	HC	EPAP* CO	NOx	Compliance Date
T2	0.4	3.0	3.0	January 1, 1981
T5	1.0	7.8	5.0	January 1, 1984

In addition, there has been proposed (FR Vol. 38, N. 136, July 17, 1973, p. 19050) a regulation which, if promulgated, would require all (including those already in service as of January 1, 1979) large (i.e., thrust > 29,000 lbs.) in-use engines of the T2 class to comply with the T2 class standards of 1979 for HC, CO, NOx, and smoke. As this would effectively require a retrofit program for the older engines (pre-1979), the compliance date was proposed to be January 1, 1983, thus allowing four years for that retrofit to be accomplished.

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*pounds of pollutant per 1000 pounds (thrust)-hours over the LTO cycle, except as noted.

**pounds of pollutant per 1000 horsepower-hours over the LTO cycle.

***pounds of pollutant per 1000 horsepower-hours at maximum power.

Section III. Emissions Control Technology

A. Introduction

This section will first describe the present aircraft emissions situation in order to give the reader some perspective of the demand that the regulations impose on the industry. At the same time, certain characteristic trends in emissions performance will be highlighted and explanations given or attempted. The need for work on control development will be obvious and the section secondly will deal with the means and effectiveness of control. Newly certified engines will be addressed along with the basic issue of newly manufactured engines and retrofit engines. In a later section (V) engines are reviewed individually with emphasis on (1) extent of exploration, (2) accomplishment, (3) estimated best performance, and (4) leadtime requirements.

B. Production Engines

The emissions performance of current production engines is presented first in order to properly focus on the problem. The data is exhibited in a format which suggests a certain pattern or trend in emissions. As it is not obvious that this should be the case, a brief analysis is performed which investigated possible governing factors. Table III-1 presents a list of all production engines and for each engine, data on the applicable class, the standards to which it must comply, the manufacturer, and an estimate of the engine's production potential which crudely measures the likelihood that the manufacturer will attempt to comply.

Production potential is not usually available in hard figures. Generally, though, the production of all engines can be grouped into four categories for EPA purposes.

Production Category	Situation
I	Engines already out of production; engines certain to be out of production by the compliance date for newly manufactured engines.
II	Engines at or near the end of their production run by the compliance date. The few, if any, units produced after that would not be sufficient to amortize the development and certification cost of a low emissions combustor.
III	Engines in the broad middle of their production run. It is possible to amortize the necessary development and certification costs for emissions control over the remaining production. It is equally possible to consider a cost-effective retrofit of the units produced prior to the compliance date; there are sufficient units to amortize that development and certification costs and to realize significant air quality gains.

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Table III-1

Emission Performance - Current Engines

Class	1979 Standard HC	1979 Standard CO	1979 Standard NOx	Engine	Size	Manufacturer*	Baseline Emissions HC	Baseline Emissions CO	Baseline Emissions NOx	Sk/Std**	Production *** after 1/1/79
T1	1.6	9.4	3.7	TFE 731-2	3,500 lbs	AiResearch	6.6	17.5	5.0	33/40	III
	(pounds of pollutant/ 1000 pound-thrust-hours/ cycle)			TFE 731-3	3,700 lbs	AiResearch	3.6	14.8	6.5	45/40	III
				JT15D-4	2,500 lbs	PWAC	12.4	34.6	3.8	14.1/43	III
				JT12A-8	3,300 lbs	P&WA	5.2	85	3.2		I
				CF700	4,315 lbs	GE	9.1	94	2.2	24/38	I
				CJ610	2,950 lbs	GE	14.7	155	2.7	44/35	I
				M45H	7,600 lbs	Rolls-Royce/ Snecma	6.0	40.7	4.2	/34	III- IV
				Viper 600	3,750 lbs	Rolls Royce/Fiat	17.2	102	1.8		I
T2	0.8	4.3	3.0	JT9D-7	46,150 lbs	P&WA	5.3	14.3	4.9	10/20	III
				JT9D-70	51,153 lbs	P&WA	1.2	5.9	5.8	5/19	
				CF6-6D	38,900 lbs	GE	3.4	10.0	7.2	13/21	III
				CF6-50C	49,900 lbs	GE	4.3	10.8	7.7	13/19	III
				RB211-22B	42,000 lbs	Rolls Royce	14.0	20.0	7.3	<21/21	III
				RB211-524	50,000 lbs	Rolls Royce	8.3	11.9	8.9	<20/20	
				Spey 511	11,400 lbs	Rolls Royce	35.7	35.7	7.8	50/30	II - III
				Spey 555	9,850 lbs	Rolls Royce	46.2	63.2	4.3	41/27	
T3	Same as T2			JT3D-1	17,000 lbs	P&WA (Smokey)*****	34.2	40.8	3.8	53/25	I
T4	Same as T2			JT8D-17	16,000 lbs	P&WA	3.1	12.8	6.8	28/30	II - III
T5 ****	3.9	30.1	9.0	Olympus	38,000 lbs	Rolls Royce/ Snecma	16.2	67	8.9	28/25	III
APU	0.4	5.0	3.0	GTCP85-98CK	290 eshp	AiResearch	0.2	7.5	6.4	N.A.	III
	(pounds of Pollutant/1000 horsepower-hour of power output)			GTCP30-92	100 shp	AiResearch	0.1	4.8	3.4	"	III
				GTCP36	192 shp	AiResearch	0.3	19.8	5.2	"	III
				GTCP660	1100 eshp	AiResearch	0.2	7.9	4.9	"	III
				TSCP700	910 eshp	AiResearch	0.2	0.8	6.0	"	III
				ST6	720 shp	PWAC	0.3	2.6	4.8	"	III
				Titan (T-39)	40 shp	Solar	0.6	21	4.4	"	III

***Abbreviations**

PWAC - Pratt & Whitney Aircraft of Canada Limited
P&WA - Pratt & Whitney Aircraft
GE - General Electric

** SK/STD - Smoke level/Smoke Standard
*** Refer to text for definition of categories
**** 1980 Compliance
***** Due for retrofit in 1980 with smokeless version

Table III-1 continued

	1979 Standard						Baseline Emissions				Production after 1/1/79
Class	HC	CO	NOx	Engine	Size	Manufacturer	HC	CO	NOx	Sk/Std	
P2	4.9	26.8	3.0	PT6A-27	715 eshp	PWAC	52	66	7.0	17/48	III
	(pounds of pollutant/1000 horsepower-hours/cycle)			PT6A-41	903 eshp	PWAC	54	81	7.2	21/48	III
				TPE331-1	705 eshp	AiResearch	86	48	6.4	18/48	III
				TPE331-2	755 eshp	AiResearch	68	44	6.2	19/48	III
				TPE331-3	904 eshp	AiResearch	55	44	8.0	19/48	III
				TPE331-5	776 eshp	AiResearch	80	52	8.9	19/47	III
				TPE331-6	776 eshp	AiResearch	68	49	8.4	20/47	III
				250	400 hp	Allison	25	128	5.3	34/50	III
				501-D22A	4680 hp	Allison	14	30	6.2	60/29	II -III
				T5321A	1800 eshp	Avco-Lycoming	2	17	6.0	17/37	IV
				PLT27	2000 shp	Avco-Lycoming	0.3	3	12.8	0/36	IV
				Dart	2280 eshp	Rolls-Royce	100	125	12.9	36/36	II
				Tyne	5500 eshp	Rolls-Royce		No data			III

IV	Engines beginning their production run shortly before or after the compliance date for newly manufactured engines. There would likely be insufficient engines built prior to the deadlines to warrant a retrofit program.

There are many formats by which to exhibit and to examine the emissions characteristics of a group of engines. Some are more desirable than others because of their simplicity and relevancy to the problem at hand. One format that readily meets these conditions is the display of engines emissions (in terms of the EPA Parameter, EPAP, defined conceptually in equation (1) below) as a function of engine rated thrust (Discussion here is limited to jet thrust type engines as most anticipated compliance problems will arise from these engines; turboprop engines as a whole will be largely successful in complying with the standards and hence do not require a detailed analysis). This format is both simple (EPAPs and rated thrust are both known for almost all engines) and relevant (it displays the standard explicitly as an EPAP value and shows its thrust dependence which is fundamental to the standards through both the thrust-based nature of the parameter and the T1-T2 class demarcation at 8,000 pounds thrust). Combustor performance based formats (e.g., combustion inefficiency vs. air loading parameter), on the other hand, are very useful for diagnostic purposes although they cannot in and of themselves show the emissions performance of an engine compared with the standards. Therefore, the emissions data of Table III-1 are also presented graphically on Figures 3, 4, and 5 for jet type engines (T classes). Table III-2 lists the symbols for the engines as they are used throughout the figures except as noted.

Table III-2

Class T1	⬟ TFE731-3
	◩ ALF502D
	◓ TFE731-2
	◣ ATF3
	● JT15D-4
	♦ JT12A
	■ CJ610-2C
	◆ CF700-2D
	▲ RB401
	⬣ M45H
	◣ Viper 600
Classes T2, T3, T4	◺ CFM56
	○ CF6-50C
	□ CF6-6D
	◇ JT9D-7
	△ JT9D-70
	◺ JT3D-7
	◹ JT8D-17
	× JT10D
	⌂ RB211-22B
	⬠ RB211-524
	◊ Spey 555
	⌂ Spey 511
	⬡ Olympus 593
	⬯ TF34

A cursory examination of these curves shows that all production engines fail to meet either two or three of the three gaseous pollutant (HC, CO, NOx) standards. None meet the HC and CO standards, while only a few meet the NOx standard. Further examination reveals an apparent trend with engine size (thrust), primarily for the pollutants which rise from incomplete combustion, HC and CO. The curves labeled "production technology" represent that trend and were derived by the procedures employed below to determine the cause of that phenomenon.

a. HC and CO Behavior

The parameter describing the aircraft standards (EPAP) can be represented by two multiplicative terms, one representative of the combustor performance (in terms of mass of pollutant per mass of fuel) and the other descriptive of the fuel consumption efficiency of the engine (in terms of mass of fuel per level of useful output), both terms being weighted over the prescribed landing - takeoff cycle:

EPAP = (combustor performance) x (fuel consumption)

or

$$\text{EPAP} = \frac{\text{mass of pollutant}}{\text{useful output}} = \frac{\text{mass of pollutant}}{\text{mass of fuel}} \times \frac{\text{mass of fuel}}{\text{useful output}}$$

$$= \text{EI} \times \text{SFC} \qquad (1)$$

Since the bulk of the HC and CO emissions are produced in the idle mode, the EPAP for these two pollutants can be approximated as follows:

$$\text{EPAP} \simeq \text{EI (idle)} \times M_f \text{ (idle)}/I \qquad (2)$$

where EI (idle) = emission index at idle; M_f = mass of fuel consumed at idle; and I = total impulse (thrust x hours) of the engine over the cycle.

From this, two important facts are ascertained: (1) The emissions performance of an engine (in terms of EPAP, the parameter upon which the standards are based) can be affected either by the combustor emissions performance (EI) or by the engine fuel performance (SFC); and (2) for HC and CO emissions, the EI and SFC at idle are paramount (M_f (idle)/I $\propto$ SFC (idle)).

It therefore appears worthwhile to investigate the apparent EPAP trend with rated thrust by first breaking the EPAP into its two components and examining their behavior with rated thrust.

Figure 6 shows the idle SFC behavior of the T classes as a function of the rated thrust.* A curve has been faired through the lower range of SFCs which represent typical modern engines. The several outliers (JT3D, JT8D, CF700, and the Speys) lie well above the curve because, being older engines, their engine cycles (primarily the bypass ratio) are inferior to the newer engines and consequently the SFCs are higher. The JT15D, shown also to be above the other curve, does possess an engine cycle comparable to that of other modern engines of similar size; however, it also appears to suffer very high inefficiencies at low power which increases the idle SFC some 30% above what might be expected.

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*All engines are considered here to operate at idle at 6% of rated thrust. Although this is not the specification of idle called for in the regulations, nor is it even desirable from a regulatory point of view, it is used here in order to reduce data scatter by putting the engines on completely the same LTO cycle (an "apples to apples" comparison).

The significance of Figure 6 appears to be that there is a characteristic trend of idle SFC with size (ignoring the older engines now) such that smaller engines (those below 8-10,000 lbs. thrust) can be expected to have a higher idle SFC which by equation (2) would be expected to exert an upward tendency on the EPAPs of HC and CO for those engines. It is of some interest to determine the basis for this, primarily with regard to newly certified engines (as modification of the SFC trend may be considered an emissions control technique). For newly manufactured or retrofit engines, there is no SFC control so that the character of this SFC trend, fundamental or fortuitous, is a moot point. A good point at which to begin is the investigation of the effect of the engine cycle on the SFC. This is demonstrated in Figure 7 wherein a theoretical calculation of SFC as a function of the engine parameters pressure ratio and bypass ratio (overall temperature ratio is assumed to be directly related to the pressure ratio) is presented and compared with typical engines. Figures 8 and 9 then show how the principle cycle parameters, the bypass ratio and pressure ratio, vary with size (rated thrust) of the engine.* Figures 7, 8, and 9 support Figure 6; that is, the faired SFC curve on Figure 6 can be closely approximated by cross plots from Figures 7, 8, and 9. For instance, at 10,000 lbs thrust, Figure 8 gives BR = 5.3 and Figure 9 gives IPR = 2.5 which on Figure 7 (interpolating) gives idle SFC ≈ 0.63 while Figure 6 gives idle SFC ≈ 0.68. Thus, it is fair to conclude that the trend seen in Figure 6 is amply explained by the engine cycle trends shown in Figures 8 and 9. The reason for these trends seen in Figures 8 and 9 is found in several technical and economic factors which are discussed below. There is nothing fundamentally rigorous about the relationship and as technology advances and economics change so also will the shape of the curves of these figures. The historical background given below will also emphasize the time dependent character of curves.

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*In Figure 8, the anomolous decrease in the bypass ratio for the over 40,000 lbs thrust range is due simply to the fact that these largest of engines are not totally new engines but are updated versions of slightly smaller thrust originals (e. g., JT9D-7 → JT9D-70) wherein the extra thrust is obtained by increasing the core pressure ratio without decreasing the physical size of the core. This effectively decreases the bypass ratio because now more air is drawn into the core at the expense of the surrounding bypass airflow. The additional core airflow permits more fuel to be added (keeping the stoichiometry the same) and this additional energy input is converted to additional thrust output. On the other hand, a totally new smaller core would accept less air so that the bypass ratio would be the same, or perhaps, even increased to obtain yet better fuel economy.

From a historical perspective, the first jet thrust type of turbine engines were low pressure ratio, zero bypass ratio (pure jet) engines with high SFCs. Although such engine cycles were very undesirable they were nevertheless unavoidable as the technology for higher pressure ratios was not available. Fans (nonzero bypass) had not yet come into existence and the advantages of them were not fully appreciated. Later, as fuel economy and noise control became considerations in addition to power and thrust-to-weight ratio, low bypass fans ($BR \leq 1.5$) such as the JT3D and JT8D were developed as growth versions of original pure jet ($BR = 0$) engines. There are a number of reasons why such engines were limited to low bypass. A close examination of figure 10 shows that the largest SFC improvements are made in the initial stages of bypass (say, $BR < 2$). For example, a $PR = 10$ engine reduces its TSFC by .136 in going from a pure jet to a $BR = 2$ fan engine, but a doubling of the bypass (to $BR = 4$) will yield a further reduction of only .083. The smaller SFC improvement (from $BR = 2$ to 4) is coupled with an even larger weight and drag penalty (from the bigger engine associated with the larger bypass) which is significant for the whole aircraft system. The only way to keep this penalty down is to have a high pressure ratio core which is capable of generating more power for the fan in a smaller system. As the original fan engines such as the JT3D were based upon cores with only moderate pressure ratio ($PR \approx 13$), weight and size restrictions as well as the technological infancy of the field dictated low bypass ratios ($BR \leq 1.5$). Later, as higher and higher pressure ratios were made feasible by technological advances, bypass ratios rose commensurately (Figure 11) to convert the higher thermodynamic efficiencies into higher propulsive efficiencies.

This background then leads to the basic question: Why do the smaller engines typically have smaller pressure ratios and lower bypass ratios than the larger engines (Figures 8 and 9)? There are a number of reasons for this. The first is economic: Large fan engines have higher initial costs and although there is a fuel penalty with the low bypass engines, the fuel savings of a large bypass engine may not pay for that larger initial cost especially if the aircraft usage is low enough (ie., depreciation cost dominates). The second is technical: High bypass engines, being heavier and more bulky, do not fit as easily into the smaller business jets and their weight creates a fuel penalty which partially offsets the fuel savings expected from the superior SFC. The third is also technical and relates to the second: It is very difficult to obtain high component efficiencies in small engines with a high pressure ratio cycle because of the very small size of the components (component size inversely proportional to pressure ratio).

Moving from the investigation of the idle SFC effect on the HC and CO EPAPs, the next component of the EPAP to explore is the idle EI. Figures 12 and 13 present the idle EIs for HC and CO of production engines as a function of thrust. An exponential regression (the solid line) through the data indicates that for conventional combustors, a roughly 50% reduction in the EI for either HC or CO can be expected as the rated thrust of the engine increases from 0 to 50,000 lbs. of the thrust.* Like the SFC behavior this will exert an upward tendency on the EPAPs for smaller engines. Again, the question which must be answered is why are these EIs dependent upon the size of the engine? There are three scale effects which are likely to have bearing on the EI behavior: (1) pressure ratio, (2) surface-to-volume ratio, and (3) air loading.

The pressure ratio at idle has a significant effect on the combustion efficiency** because, first, combustion at higher pressure enhances in particular the $CO \rightarrow CO_2$ reaction rate and also many of the hydrocarbon reactions, second, the higher combustor inlet temperatures associated with the higher pressure*** increases the fuel droplet evaporation rate, thereby enhancing hydrocarbon reactions, and third, the higher pressure into the combustor permits a greater pressure drop across the fuel injection which can be used to shatter the fuel drops (airblast). The significance of the pressure ratio to good combustion efficiency is reflected in rig-to-engine pressure correction formulas used by NASA (reference 59):

$$\text{HC (eng)} = \text{HC (rig)} \times \frac{P(\text{rig})}{P(\text{eng})}$$

$$\text{CO (eng)} = \text{CO (rig)} \times \left[\frac{P(\text{rig})}{P(\text{eng})}\right]^N$$

Figure 14 plots the combustion inefficiency ($1-\eta_c$) vs. the idle pressure ratio for production engines. Although there is considerable scatter indicating the effect of the other factors on the combustion process, the trend line (an exponential regression) shows roughly 30% decrease in inefficiency between the lowest idle pressure ratio (1.5) and the highest (4). Figures 15 and 16 show the EI performance of the individual pollutants vs. the idle pressure ratio.

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*These regressions ignored the JT3D, the Spey, the CF700 and the CJ610 engines. The emissions from these engines are not representative of what is achievable by modern production engines, as they represent old technology. The RB 211's and the M45H were also ignored because of unusually high emissions, especially HC. These are modern production engines, but their emissions are not representative. The uniformly high emissions level of the Rolls Royce engines may be due to the tendency of these engines to have large idle air loading parameters (see discussion later in this segment); however, this cannot explain the high HC, CO emissions of the RB211-524 whose air loading parameter at idle is quite modest.

**Combustion efficiency = $\eta_c = 1 - [.875 \times \text{EI (HC)} + .2322 \times \text{EI (CO)}] \times 10^{-3}$

***Ideally, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{.286}$

The second potentially significant parameter is the surface-to-volume ratio. This is merely a measure of the relative amount of surface area to which a given flow is exposed. The significance to combustion arises because the liner surface must be cooled by a film flow of air heated only to the compressor exit temperature and this cooling air is capable of quenching certain reactions which demand a higher temperature to proceed, in particular the $CO \rightarrow CO_2$ reaction. Thus, a combustor with a high surface-to-volume ratio would expose a greater portion of its flow to the vicinity of the liner surface, thereby quenching a greater fraction of the $CO \rightarrow CO_2$ reaction than would a low surface-to-volume combustor which would then leave more CO in the exhaust. A large surface-to-volume combustor would not normally affect HC emissions too much unless the fuel nozzle were spraying fuel directly onto the liner wall in which case the problem is not so much the surface-to-volume ratio as it is the fuel nozzle. Figure 17 shows the effect of S/V on combustion inefficiency. The trendline, again an exponential regression, shows an effect comparable in magnitude to the pressure ratio variation. Figures 18 and 19 demonstrate that the S/V effect is almost exclusively on the CO emissions and not the HC emissions, as discussed above. There is a point of confusion, however. Figure 20 shows that there is a general trend between higher idle pressure ratios and lower S/V so that in either Figures 14 or 17 the underlying physical effect may not be the parameter labeled on the abscissa, but rather the other one.

The third potentially significant parameter is the air loading parameter (52) a semi-empirical factor defined by

$$\Omega = \frac{\dot{M}_a}{P^{1.8} \times f(T) \times V}$$

where

$$f(T) = \exp T_3/540$$

Being an empirical type of expression, there may be some variation in the definition among various users. The terms in this expression are:

$\dot{M}_a$ = combustor air mass flow rate (lb/sec)

P_3 = combustor inlet pressure (atmospheres)

V = combustor liner volume (ft^3).

T_3 = combustor inlet temperature (°R)

The expression represents a rough approximation of the extent to which the fuel combustion should have proceeded. Specifically,

$$\Omega \sim \frac{1}{(\text{reaction rate}) \times (\text{residence time})}$$

Thus, larger values of Ω means that the product of the rate times the time is small, indicating that either the reaction rate or the residence time or both are small and that, in any case, the reaction cannot have proceeded very far before the fuel exits the combustor. High values of combustion inefficiency would then be expected. On the other side of the coin, smaller values of Ω indicate that the reaction should have proceeded quite far before the fuel, what is left of it, exits. Low values of combustion inefficiency would be expected.

A combustor for any given engine will experience a range of Ωs depending upon the power level of the engine, higher power means lower Ω. The actual range of Ω from the high power setting to the low will vary between engines and is dependent upon such design variables as the compressor pressure ratio, the size of the combustor, and the idle power setting level.

The emissions performance of different control techniques (for HC and CO emissions) can then be investigated systematically by comparing the combustion inefficiencies at equal values of the air loading parameter.

Figure 21 presents the combustion inefficiency $(1 - \eta_c)$ vs. the air loading parameter (Ω) for idle only. The regression line through the data verifies the trend expected and the correlation coefficient of 0.43 indicates that this variable alone is better than either IPR or S/V. However, there is again a point of confusion: Just as there was found to be a correlation between IPR and S/V, similarly there are found to be correlations between Ω and both IPR and S/V as shown in Figure 22 and 23. Thus, the effects of these three parameters are not totally independent. The air loading parameter in particular obviously accounts for the pressure effect on the combustion process and to that extent acts as a substitute for IPR; however, it does independently account for the residence time effect which neither of the other parameters do.

There are certain drawbacks to Ω and S/V as correlation parameters. What is needed here is a correlation parameter that is both relevant (i.e., has a bearing upon the combustor emissions) and also characteristic of the engine so that it remains constant for a given engine regardless of the combustor modifications employed to reduce emissions. All three of the parameters discussed here are relevant, but two are combustor oriented (S/V and Ω through the residence time effect). The values of these parameters are likely to change, perhaps appreciably, in a low emissions design, making it difficult to compare the old and the new. On the other hand, such parameters are excellent design tools for they suggest what modifications should be made in order to achieve the desired goal (e.g., increase V to reduce Ω at idle to improve the combustion efficiency). The third parameter (IPR) is, of course, an engine oriented parameter and consequently it meets both of the requirements above. Of course any engine condition parameter has the drawback that for a few category 1 concepts (defined in part C) such as airbleed, that parameter will change in going from the production version to the low emissions version, whereas a combustor oriented parameter (e.g., S/V) would remain constant, as desired. Therefore, an engine based parameter is not perfect.

In summary then, the idle pressure ratio (IPR) will be used to compare the HC and CO emissions performance of the various control concepts with that of production type engines. Figures 15 and 16 represent the baseline combustor performance against which the comparisons are to be made. It is necessary also to demonstrate that the scale effect represented by Figures 15 and 16 does indeed explain quantitatively the EI trend alluded to in the discussion of Figures 12 and 13. By combining Figures 15 and 16 with Figure 9, one obtains the dashed lines in Figures 12 and 13. As can be seen, they approximate reasonably well the regression curves. Furthermore, using the approximation of equation 2, Figures 6, 12, and 13 can be combined to derive the "production trend lines" shown in Figures 3 and 4. Following the several steps leading up to these production trend lines, one can see that the root of these trends is the characteristic tendency towards larger engines having higher bypass and pressure ratios (which affect the SFC) and the fact that combustion efficiency improves with higher operating pressures (i.e. pressure ratio).

b. NOx Behavior

Oxides of nitrogen, or NOx, arise from the oxidation of atmospheric and possibly fuel-bound nitrogen in lean, hot combustor conditions wherein there is both oxygen and activation energy available. Thus, NOx is primarily a product of high power operation although over the EPA LTO cycle, only 50-60% of the total NOx is produced at climbout and takeoff: At idle and approach the longer times-in-mode compensate for the lower NOx formation rate. It is, therefore, impossible to make the kind of single mode approximation represented by equation (2): All four modes must be considered.

Figure 5 presented the NOx EPAPs for production engines. As presented, two facts become apparent. First, all but a few T1 class engines fail the standard. Second, throughout most of the thrust range the average EPAP is relatively constant (≈ 6-7) with a scatter of ± 2, while at the lowest thrust levels (T1 class), a precipitous drop in $\overline{\text{EPAP}}$ occurs. Once again equation 1 can shed light on this behavior although the simplicity of equation 2 is not available. For reference,

$$\text{EPAP} = \text{EI} \times \text{SFC} \qquad (1)$$

$$\text{EPAP} \approx \text{EI (idle)} \times M_f \text{ (idle)} I \qquad (2)$$

Figure 24 shows the rated SFC trend of the T classes with size (thrust). Here, rated SFC, not idle SFC, is considered as NOX is predominantly a high power pollutant, although as indicated above, not exclusively. The trend to lower SFCs for larger engines would, by equation 1, contribute to a reduction in the NOx EPAP unless the EI trend is such that it counteracts the SFC trend. That such is the case is readily seen in Figure 25 showing EI (NOx) increasing with rated thrust. Once again the question must be asked: Are these trends with size a fundamental characteristic or a circumstantial coincidence that can be overridden as necessary to achieve a more favorable climate for low emissions?

The SFC trend has been explored before in the HC and CO discussion and the understanding obtained then is applicable in this instance with, however, reference to the rated (full power) condition rather than the idle. Specifically, the theoretical calculation of Figure 10 can be combined with Figures 8 and 28 specifying the trend in the cycle parameters with size to generate approximately the faired curve on Figure 24. This then shows how the SFC trend with size (Figure 24) is caused, once again, by the engine cycle trend with size (Figures 8 and 28). In any event, SFC is not a variable to deal with for newly manufactured engines (NME); however, it certainly is for newly certified engines (NCE) for which there is a choice in the engine cycle.

To explore the EI(NOx) trend, a proper starting point is a summary of all the potential influences on NOx formation within the combustor. From a chemistry point of view, the following parameters are understood to be relevant:

(1) P_3*, the combustor inlet pressure (essentially the pressure throughout the combustor);

(2) $\tau_{res,p}$, the residence time of the gas in the primary combustion zone, at peak temperature;

(3) ϕ_p, the equivalence ratio of the primary combustion zone (the equivalence ratio is the ratio of the actual fuel to air mixture to the stoichiometric, hence a measure of both the excess O_2 and the flame temperature T_f, among other things.

Because of the relationship between these parameters and other combustor parameters, these parameters can be replaced by the other, related parameters, as convenient. The most notable substitute parameters are:

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*See Appendix C for the definition of the combustor stations.

(1) T_f, the flame temperature,

(2) T_4, the combustor exit temperature (or turbine inlet temperature),

(3) V_{ref}, the reference velocity,

(4) ϕ, the overall combustor equivalence ratio, and

(5) T_3, the combustor inlet temperature (or compressor discharge temperature).

Despite the many relevant variables, it has been discovered (by Lipfert) that the NOx formation (as described by EI(NOx)) can be correlated quite accurately with only one variable, T_3, as shown in Figure 26. This empirical relationship holds very well for existing engines, despite its simplicity, because existing engines are designed so similarly that for all practical purposes T_3 (or its equivalent, P_3) is the only independent parameter. Specify that parameter and all the other parameters are reasonably well determined. Because T_3 and P_3 are related by the adiabatic relation,

$$\frac{P_3}{P_1} = \left[\left(\frac{T_3}{T_1} - 1\right)\eta_c + 1\right]^{\frac{\gamma}{\gamma - 1}}$$

(Where T_1 and P_1 are atmospheric conditions and η_c is the compressor efficiency.), the Lipfert correlation can also be presented as in Figure 27. Also, the rated compressor pressure ratio (defining P_3 at takeoff) tends to be higher for the larger engines as is evidenced by Figure 28. There is nothing fundamental about this and in fact the same can be said of its significance as was said earlier of Figures 8 and 9: "The reason for this (*the relationship with size*) is found in several technical and economics factors... There is nothing fundamentally rigorous about the relationship and as technology advances and economics change so also will the shape of the curves of these figures."

From the faired curve of Figure 28, it is possible to backtrack using the Lipfert correlation (Figure 27) to arrive independently at an approximation (the dashed line) to the regression (the solid line) drawn on Figure 25. From the Lipfert curve (Figure 27), the rated pressure ratio curve (Figure 28), the rated SFC curve (Figure 24), and the approximation explained in Appendix D with sample calculation, the production technology trend line in Figure 5 is arrived at showing a self consistent set of curves with the data.

Up to now the examination of the NOx EI data using either T_3 or P_3 as a correlating parameter has been satisfactory in view of the accuracy of the correlation (Figure 26). However, in examining low NOx technology this proves to be inadequate as, in that case, the combustor design and operating environment will differ greatly between combustors so that one can anticipate a considerable increase in the scatter. These combustor differences should be treated as independent variables leading then to more complicated correlations than have been successful in the past. This shall be demonstrated as the low emissions data are presented and analyzed. The difficulty of the T_3 correlation in adequately extrapolating NOx data to new conditions suggests its replacement by the correction formula offered by NASA in reference 59 (ECCP summary to EPA). This correlation, of course, also has its limits of applicability which may be exceeded in the course of analysis. In the next part, the investigation of low emissions techniques will begin.

C. Emissions Control for Existing Engine Types

As discussed in part B, the emissions performance parameter used by the EPA (EPAP) can be affected by both changes in the specific fuel consumption (SFC) and in the combustor emissions performance (EIs) (see equation (1)). Furthermore as evidenced in Figures 7 and 10 the SFC is controlled by engine cycle parameters (pressure ratio, bypass ratio, and turbine inlet temperature) over which there is little or no chance of control in existing engines for to change any of these parameters significantly would imply a new engine, different from the original. It follows then that for newly manufactured engines (NME) and retrofit engines effective emissions control can be achieved only through combustor control. This part addresses the concepts used in combustor emissions control, their problems and performance. Some of these schemes are more esoteric than others and, as such, are far from proven. Others are more modest in approach and are more readily adapted into present-day flight hardware. Unfortunately these latter techniques, while often very effective against the low power pollutants (HC and CO), usually cannot appreciably improve NOx emissions. Furthermore, while many of these control techniques are simple in concept, many are nonetheless difficult to apply in practice because they are often detrimental to the combustor performance in non-emissions related areas such as altitude relight, durability, etc. Lastly, some concepts are better suited to one class of engines than another for various reasons, technical and economic. Because of this diversity among the potential control concepts, it becomes advantageous to evaluate them with respect to several factors. From the remarks above, the primary factors should be:

(1) development status

(2) control capacity

(3) complexity of the development process

(4) application

For each factor, a scale of one to four is taken to describe the rating or relative position of a control technique. The factors and the meaning of the numerical assignments are given in Table III-3. In addition, for the emissions performance category the particular pollutants that are controlled by a given technique are noted while for the applications factor, those specific classes of engines for which a given limited control technique is apropos are also noted.

Table III-4 tabulates the various control schemes and gives their ratings for each of the four factors.

A description of each of the emissions control techniques listed in Table III-4 is given in Appendix C. The descriptions briefly tell what it is, how it works, what pollutants it controls and by what physical mechanisms, and what the problems or drawbacks with it are.

The study of the emissions performance of these concepts will be conducted by considering the performance in terms of grouping by category of complexity (the third factor). Thus all known data for the performance of control schemes of category 1 (trivial complexity), say, will be displayed, then that of category 2, etc. The displays will be of the emissions indices (EI) as a function of pressure ratio (idle for HC and CO, rated for NOx) in accordance with the conclusions reached in the investigation of the behavior of production engines earlier in this section.

A summary of the emissions performance of existing engine types utilizing the best control techniques of technology complexity categories 1-3 demonstrated in those engines is presented in Table III-5 and in Figures 29-33. As brought out earlier in the report, concepts of complexity categories 1 and 2 essentially control HC and CO while category 3 technology adds control of NOx (the glaring exception being water injection, category 2). The appearance of HC and CO control by category 3 technology in Table III-5 arose because category 1 or 2 concepts for HC and CO control have been used in tandem with the category 3 concept in order to effect control of all three pollutants. Figures 29-33 reflect this fact; there is no consideration of the NOx performance of categories 1 or 2, nor is there consideration of the HC and CO performance of category 3. Generally a number of concepts of a given category have been examined in particular engine types but only the best appear in the table and in the figures. The demonstration has either been engine testing or rig testing simulating engine operation. In the figures, trend lines have been drawn following the procedure set forth in this part. It is worth repeating here that these trend lines do not represent

Table III-3

Ratings of Control Techniques

Factor	Rating			
	1	2	3	4
Development Status	Immediately available for production in most engines; little or no difficulty in the certification process.	Governing principles thoroughly understood; application to a specific engine requires only tuning of the concept to the engine consistent with the performance requirements of the engine; no major difficulties expected; little difficulty in the certification process.	Basic concept is understood, but a fair amount of work is involved in developing flight-worthy hardware in any application; a number of design points are not adequately worked out; Certification will be quite thorough.	Concept is understood in general physical and chemical terms, but little or no actual testing in engine type hardware has been done; concept is essentially in the research stage; a number of basic problems are unresolved.
Control Capacity	Effective in reducing emissions(for which the technique is intended)to regulation levels in most engines, including those for which the operating conditions and/or the SFC characteristic may be deleterious to compliance.	Effective in reducing emissions (for which the control is intended) to the regulatory levels in representative, modern engines (good SFC characteristics and for HC, CO, at least, favorable operating conditions).	Somewhat effective in reducing emissions (for which the control is intended), but not necessarily to the regulatory levels.	Effective in reducing emissions only in selected engines, either because it relies upon conditions unique to that engine or because it is capable of controlling only the dirtiest engines (See Application below).

Table III-3 (cont.)

Category	Rating			
	1	2	3	4
Complexity of the Development Process	Trivial complexity; little or no difficulties encountered in development of the concept on most engines for which it would be intended.	Only some minor to moderate difficulty anticipated in the development of the concept or an engine, usually associated with the combustor durability or performance; development straightforward, although some time is required.	A number of difficulties must be overcome in developing flightworthy hardware; preservation of other design criteria requires a compromise with the full potential of the emissions control device.	A number of basic problems are unresolved and are expected to yield to solution only with difficulty; in fact, perhaps not all of the development problems have even been identified.
Application	Generally appropriate for all classes of engines (T1 - T2,* P2).	Appropriate for all classes of engines, but with some difficulty in development in some engines of one or more classes due to the characteristics of that class or special characteristics of those particular engines.	Appropriate generally only for one class although it might be incorporated into one or more engines of another class.	Appropriate only for a specific engine or two within a given class.

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*T3 and T4 engines are included here in the T2 group since the standards as promulgated, are identical and the class distinction exists only for the purpose of setting early smoke standards.

Table III-4

Ratings of Emissions Control Techniques

Control Techniques	Development Status	Control Capacity	Category of Complexity	Application*
Fuel atomization	1	4(HC, CO, NOx)	1	4
Idle speed	1	3(HC, CO)	1	1
Airbleed	1	3(HC, CO)	1	1
Air-assist (external)	1	1(HC, CO)	1	1
Fuel-sectoring	2	2(HC, CO)	1	2
Nozzle design	1	4(HC, CO)	1-2	4
Air blast (Aeration)	2	1(HC, CO)	2	3***
Combustor length	1	4(HC, CO)	2	4
Water injection	1-2	1(NOx)	2	3(T2)
Rich primary	2	3(HC, CO)	2	2
Lean primary (1)	2	3(HC, CO)	2	
Delayed dilution	2	3(HC, CO)	2	2
Premix (1)	2	2(HC, CO)	2	2-3****
Lean Primary (2)	3	2(NOx)	2-3	2
Fuel Staging	3	2(NOx)	2-3	2
Premix (2)	3-4	3(HC, CO, NOx)	3-4	1
Variable Geometry (Air staging)	4	1-2(HC, CO, NOx)	3-4	2
Catalysis	4+	1(HC, CO, NOx)	4	1

* classes T2, T3, T4 are considered here as a single group

** Divided chamber fuel staging; staging by divided nozzles within a single combustor may be appropriate for small engines.

*** Higher pressure ratio engines only

**** Application easiest in those limited cases in which combustor length is not constrained (e.g., Allison 250)

Table III-5

Technology Advances

Engine	Manufacturer	Size	Concept	Complexity Category	Level Achieved HC(EPAP)	Level Achieved CO(EPAP)	Level Achieved NOx(EPAP)
Class T2*							
Standard					0.8	4.3	3.0
CF6-50C	GE	49,900 lbs.	Sector Burning	1	0.3	5.3	7.8
			Double Annular Combustor (Fuel Staging)	3	0.3	3.0	4.3
CF6-6D	GE	38,900 lbs.	Compressor Bleed	1	1.7	8.0	7.4
CFM56	GE/Snecma	22,000 lbs.	Baseline**		1.7	12.8	4.7
			6% Idle		1.3	11.1	3.7
			Sector Burning	1	0.9	10.9	4.8
			Modified Combustor with Sector Burning	2	0.2	9.7	4.8
JT9D-7	P&WA	46,150 lbs.	Air Assist	1	1.4	9.4	4.9
			Aerating Nozzle (Air Blast)	2	0.2	1.3	4.6
			Hybrid Combustor (Fuel Staging)	3	0.7	3.3	3.5
JT9D-70	P&WA	51,150 lbs.	Air Assist	1	0.3	3.9	5.8
			(Aerating Nozzle) (Air Blast)	2	0.2	2.3	4.8
			With Water Injection	2	0.2	2.3	1.9
			Fuel Staging/Premix	3	0.7	3.5	3.8
JT10D	P&WA	~23,000 lbs.	Baseline**			No Data	
JT3D-7	P&WA	19,000 lbs.	Aerating Nozzle*** (Airblast)	2	18.0	26.2	5.6
JT8D-17	P&WA	16,000 lbs.	Air Assist	1	1.2	10.5	7.1
			Aerating Nozzle (Air Blast)	2	0.8	5.0	7.1
			Vorbix (Fuel Staging)	3	0.2	9.0	4.3

* Includes special classes T3 and T4

** New engine; baseline represents the first design against which to compare later modifications.

*** Designed for smoke standard only; no attempt to comply with 1979 gaseous pollutant standards.

Table III-5 continued

Engine	Manufacturer	Size	Concept	Complexity Category	Level Achieved HC(EPAP)	Level Achieved CO(EPAP)	Level Achieved NOx(EPAP)
Class T2*							
RB211-22B	Rolls Royce	42,000 lbs.	Unknown	1-2	0.7	5.6	6.8
RB211-524	Rolls Royce	50,000 lbs.	Unknown	1-2	0.5	3.7	7.1
Spey 511	Rolls Royce	11,400 lbs.	Unknown	1-2	5.0	20.7	7.4
Spey 555	Rolls Royce	9,850	Unknown	1-2	6.0	23.4	4.2
Class T1							
Standard					1.6	9.4	3.4
TFE731-2	AiResearch	3,500 lbs.	Air Assist (270 psig)	1	0.5	6.7	5.6
			Piloted Airblast	2	0.7	11.6	5.4
			Premix/Mod 3	3	0.6	9.2	2.7
ATF3	AiResearch	~5,000 lbs.	Baseline**		5.8	16.9	4.1
JT15D-4	PWAC	2,500 lbs.	Compressor Bleed (Idle + Approach - 10%)	1	5.2	30.0	4.5
			Airflow Distribution, Injector Mod	2	0.14	10.9	4.8
CJ610	GE	2,950 lbs.	Nozzle Mod	1	2.5	154.5	2.7
			Airflow Distribution	2	--	135.7	2.7
CF700	GE	4,300 lbs.	Nozzle Mod	1	1.6	94	2.2
			Airflow Distribution	2	--	82	2.2
M45H	Rolls Royce	7,600 lbs.	Unknown	1-2	0.5	5.3	3.3
RB401	Rolls Royce	5,400 lbs.	Baseline**		0.2	10.2	3.6
ALF502D	Lycoming	6,500 lbs.	Baseline**		3.3	23.4	3.5
			Air Blast****	1****	2.3	11.9	4.1
			Air Blast/Combustor Mod	2	1.5	11.9	3.0
			Flightworthy hardware	2	2.6	17.8	3.2
JT12A	P&WA	3,300 lbs.				No data	

****Nozzle modification, no airflow redistribution

Table III-5 continued

					Level Achieved		
Engine	**Manufacturer**	**Size**	**Concept**	**Complexity Category**	**HC(EPAP)**	**CO(EPAP)**	**NOx(EPAP)**
Class P2							
Standard					4.9	26.8	12.9
TPE331-2	AiResearch	755 eshp	Primary Orifice Only at Idle (Injector Mod)	1	4.3	18.8	7.7
TPE331-3	AiResearch	900 eshp	Primary Orifice Only at Idle (Injector Mod)	1	3.6	12.8	8.9
T5321A	Lycoming	1800 shp				No Data	
LTP101	Lycoming	620 eshp	Injector Mod	1	8.3	25.6	6.1
			Airflow Distribution	2	3.6	17.5	6.2
PLT27	Lycoming	2000 shp				No Data	
250	Allison	400 shp	Premix Combustor	2	1.2	13.8	9.3
501D-22A	Allison	4680 shp	Reverse Flow Combustor (Airflow Distribution)	2	0.3	4.6	7.3
			Fuel Staging	3	0.6	5.7	7.2
PT6A-27	PWAC	680 shp	Improved Primary Mixing/ Airflow Distribution	2	4.8	31.6	-
PT6A-41	PWAC	900 shp	Airflow Distribution	2	1.8	16.6	8.3
Dart	Rolls Royce	2280 shp	Duplex nozzles	1	66	95	1.4
Tyne	Rolls Royce	5500 shp				No Data	

Table III-5 continued

Engine	Manufacturer	Size	Concept	Complexity Category	Level Achieved HC(EPAP)	CO(EPAP)	NOx(EPAP)
Class APU++							
Standard					0.4	5.0	3.0
GTCP85-98	AiResearch	290 eshp	Change in Spray Cone Angle (Nozzle Mod)	1	0.1	3.7	6.9
GTCP30-92	AiResearch	100 shp	Production Combustor	-	0.1	4.8	3.4
GTCP36	AiResearch	192 eshp	Airblast	2	0.04+	5.0+	5.4
TSCP700	AiResearch	910 eshp	Production Combustor	-	0.2	0.8	6.0
			Water Injection	2	--	1.6	3.0
GTCP660	AiResearch	1100 eshp	Production Combustor	-	0.2	7.9	4.9
Titan (T39)	Solar					No Data	
ST6	PWAC	720 shp	Airflow Distribution	2	0.02	1.0	5.2

+ Estimated from incomplete data.

++ A number of production engines have been quoted here because while no improvements have been reported, those engines comply with the HC standard and perhaps the CO standards and thus are at least partially successful.

any particular fundamental constraint upon emissions performance. For existing engines, though, the engine cycle is fixed and therefore so is the SFC characteristic (Figures 7, 8, 9, 10, and 24). By equation 1, then, the only remaining mechanism by which to influence the EPAP value is the combustor emissions performance (EIs). To this extend there is a fundamental constraint on the EPAPs achievable for existing engines: Only the combustor performance can be controlled.

a. HC and CO Emissions

For this part concepts with technology categories 1 and 2 will be addressed as they only control HC and CO production. First the performance of category 1 will be examined, then that of category 2. Category 1, from Table III-3, involves only trival complexity to implement and thus may be considered to include the ideas that are the least expensive and most quickly implemented.

Figures 34, 35, and 36 present the HC and CO emissions performance of the best category 1 techniques applied in current engine combustors (rig or engine). The specific techniques employed in each engine combustor are those listed in Table III-5 and in Appendix B, the data bank. Regressions of the data are shown and represent the "average" performance of the group; also shown are the regressions from the production engine curves, Figures 14, 15, and 16.

It should be understood that control concepts with data points above that "average" do not necessarily constitute inferior concepts. In the discussion on the selection of an appropriate parameter with which to compare emissions performance (IPR was chosen, S/V and Ω are not used), it was shown that there are other effects besides IPR which impact on the final emissions. Some of the effects can be modified through selective design (e.g., V changes to change Ω) but only to a point, for there are other competing design criteria (e.g. V changes affect altitude relight). Thus, it is possible that despite all attempts to optimize design, the combustor of a specific engine may nonetheless exhibit relatively poor emissions characteristics because of inherent features in the combustor that cannot be completely eliminated.

For example, the CFM56 has a higher than average EI(CO) in its category 1 application considering the IPR of the engine. The reason is due largely to its short (low volume) combustor which leads to a fairly short residence time (reflected partially in the idle $\Omega = 0.66$) which in turn causes high CO emissions because there is inadequate time for the $CO \rightarrow CO_2$ reaction to approach equilibrium. There is little the designer can do to increase appreciably the volume of this combustor (category 2 work) without incurring considerable problems with engine envelope (cost and weight penalty) and liner cooling or turbine parts (durability penalty as cooling is adversely affected by the requirement that now a larger surface area must be cooled by the same amount of air - an increase in the cooling air would mean less air for temperature pattern adjustment before the turbine creating a durability problem there).

Figures 37, 38, and 39 present the HC and CO emissions performance of the best technology rating 2 technology. The regressions for that data, the category 1 data, and the baseline data are labeled. In these figures, the JT3D data have not been included although the low smoke work now undergoing service evaluation constitutes category 2 work. The reason is basically that work was not directed towards compliance with the 1979 standards and does not necessarily reflect the best that can be done with that combustor. Again the specific concepts which are involved are those listed in Table III-5.

b. NOx Emissions

The discussion here shall be generally limited to category 3 concepts. The only category 2 technique that is capable of controlling NOx is water injection which is recognized to be extremely effective. However, as its use would normally be considered a stop-gap measure, only a little space will be devoted here to a study of its performance; the remainder will be devoted to category 3 technology.

Category 3 technology, and for that matter, water injection, inherently control mainly NOx, leaving HC and CO control to the schemes of category 1 and 2. In fact, NOx control concepts frequently encourage a compromise between NOx and CO emissions, letting CO increase in order to further reduce NOx. While not ideal, this is at least acceptable so long as CO control techniques are independently available to keep the levels tolerable.

Figure 40 shows the NOx emissions performance of the known category 3 concept studies presented on the modified Lipfert plot. It is important to realize that there is nothing absolute about these curves. The existing techniques are generally quite capable of lower NOx levels simply by retuning the air patterns or fuel flow schedules. However, this would result in exponentially increasing CO levels which, at the present performance (and likely the future performance) of category 1 and 2 technology, would yield unacceptably high CO levels (i.e., in excess of the standard). Thus, the performance level of this NOx technology is based in large measure upon the CO standard and the limits of available CO control.

The distortions of the curves from a line with a monotonically varying radius of curvature are due to the fuel staging arrangements wherein at approach power, in particular, there are a variety of options available for the fuel scheduling which lead to radically different emissions levels. At the two power limits at which optimum conditions are better defined, it is seen that the low power NOx is comparable to production combustors while the high power NOx is lower, a result of the use of lean burning. At approach power, in particular, the JT9D-70 is seen to have high NOx emissions, higher, in fact, than production engines (Lipfert). This is a result of trying to keep the CO down and to preserve stable operation at that power. The variability between rich and lean operation and the stability of the latter is achieved by the fuel staging.

The capability of water injection is presented in Figure 41. The spread reflects the fact that almost any level of NOx is achievable if desired short of putting the flame out altogether. The penalty paid for high water injection rates is excessive CO production which is demonstrated in Figure 42.

With this information of the "average" performance of the different categories as represented by the regression lines, it is possible to establish the EPAP trends. This serves to give an indication of the potential of a given level of technology (complexity) to achieve compliance with the standards when installed in existing engine types. This is only an indication, however. First, a number of concepts tried on various engines do not represent necessarily the best concepts of that category and yet those data affect the location of the regression or "average" line. If the few best techniques had been tried on all engines, the overall performance levels would have been better. Second, a given control concept, although potentially very good, may not have been fully optimized for a particular application before being abandoned. Hence, that too will raise the average performance level above that which is possible.

Using the combustor performance curves on Figures 35, 36, 38, and 39, combining with the engine data on Figures 6 and 9, and using the approximation of equation (2), one can establish the trend lines shown in Figures 29 through 32. One could adopt the same procedure in the derivation of a trend line for NOx (using Figures 40, 24, and 28). However, this would not be particularly accurate in view of the dependence of the EI(NOx) value upon the power level as well as upon the pressure ratio. For example, the data point obtained at the approach power of the JT9D-7 engine (eg., PR = 10) would be totally invalid if applied to, say, the climb power point of a low pressure ratio engine also operating at PR = 10. The two engines, being at different power modes, would have quite different temperature patterns due to fuel staging differences which would result in different EI(NOx) despite the same combustor pressure. One procedure that improves upon the method is presented in Appendix G. The resulting trend is drawn on Figure 33.

D. Newly Certified Engines

1. Introduction

In this part a review of the technology applicable to newly certified engines is presented. The analysis conducted is similar to that conducted for the T classes of newly manufactured engines (NME) and in fact much of the data is drawn from those figures. The major extension of the analysis is the requirement to specify a new SFC curve. This extension is necessary because of the very fact that newly certified engines (NCE), which imply newly designed engines, are under consideration. These engines are more capable of low emissions because of the greater degree of freedom available (1) in the selection of the engine cycle (affecting the SFC) and (2) in the design of the combustor and ancillary systems (permitting more advanced technology to be used, giving lower EIs). From equation (1), it is evident that this freedom of control of both the SFC and the EI offers the maximum potential for effective control. In addition an analysis is conducted on the so-called "prop-fan" engine concept (Reference 61 and 62) which appears to be an attractive alternative to the turbofan engine for fuel conservative aircraft of the future.

2. T1-T2 standards

As remarked in part C, category 1 and 2 technology offer effective HC and CO control, but little or no NOx control, whereas category 3 technology contains concepts which are capable of achieving a fair degree of NOx control although sometimes at the sacrifice of some HC and CO control (requiring, therefore, category 1 and 2 techniques to be used in conjunction so as to retain low HC, CO characteristics). Category 4 technology should be capable of optimum control of all three pollutants, but as said at the beginning of the report, so little has been done that accurate reporting is not possible. Furthermore, the infancy of the development work and the long leadtime required render category 4 useless insofar as early compliance is concerned.

The category 1 and 2 technology that is available to newly manufactured engines (NME) for HC and CO control is already adequate to allow future engines to comply with the presently promulgated HC and CO standards for T2 class newly certified engines (NCE). It cannot then be expected that there will be much further development effort. The best demonstrated EI performance for HC and CO is represented by the air-assist (category 1) and airblast (category 2) points from Figures 35, 36, 38, and 39 and is shown again in simplified form in Figures 43 and 44.

Without the availability of category 4 technology (which should be capable of ultra-low NOx levels) only category 3 technology remains to achieve NOx control. Water injection, a category 2 concept, is not considered here because it is an add-on type of solution with a number of operational drawbacks such that if an alternative is available, that will be preferred; water injection certainly is available in any case. Category 3 potential is known, as with categories 1 and 2, from the development work done in pursuit of the newly manufactured engine (NME) standards. Unfortunately, it is also known (part C) that its performance is inadequate to allow the large, modern T2 class engines to comply with the existing NME standards, so that it is dubious whether it can do better for newly certified engines (NCE) in which the NOx environment is expected to be much worse (owing to the higher pressures, see Figure 27). On the other hand, some SFC improvement is expected so that the net effect may not be too bad.

The other major technology change affecting the levels of the NCE standards is modification of the thermodynamic cycle to improve fuel economy (SFC). Figure 45 shows both the rated TSFC performance and the idle SFC performance projected for newly certified engines. The rated TSFC curve is based upon the performance of the following hypothetical engines:

(1) Thrust = 3500 lb. (TFE 731 size)
Bypass ratio (β) = 4
Pressure ratio (PR) = 20
Turbine inlet temperature (TIT) = 2680°R

(2) Thrust = 47,000 lb. (JT9D size)
β = 8
PR = 40
TIT = 2860°R

The cycle parameters for each engine have been selected on the basis of current trends in engine design. Actual designs in the future, however, may differ considerably from these estimates because of the existence or non-existence of a certain technology and because of redirected economic priorities which may reorient the trends now perceived. Specifically, the parameters for the small engine are based upon the following points:

(1) Pressure ratio is limited by the physical size of the high pressure components. A very high pressure ratio implies very small dimensions in small engines as the air is dense once pressurized. This leads to high component inefficiencies arising from various, mostly aerodynamic, reasons. At present, engines of this size have pressure ratios up to 13-15.

(2) Along with the increase in pressure ratio is the concomitant increase in the turbine inlet temperature. This occurs because of the need to maintain a proper margin between the compressor discharge temperature (which rises with higher pressure) and the turbine inlet temperature. An inadequate margin results in too large an engine (insufficient work per pound of air). At present, engines of this size (pressure ratio $\sim$ 15) have turbine inlet temperatures of up to 2300°R.

(3) Bypass ratio is limited by the core operating parameters (temperature and pressure) as the fan cannot extract more power than is being produced by the core. This limit is not reached in general practice, nor is it here, because of possible SFC degradation at cruise conditions and because of the weight and cost of a very large fan. Current engines of this size have bypass ratios of less than 3, although large Tl type engines ($\sim$ 6000 lbs. thrust) have bypasses up to 6.

For the large engine, the following points were considered in the selection of the engine cycle:

(1) The pressure ratio is generally made as large as is practicable as small size is not a limiting factor. Factors which do limit the pressure ratio are the maximum engine temperature limit and the mechanical efficiency achievable. Pressure ratios of 30 are now in service and compressors capable of ratios of 40 to 50 are being considered. The lower level was selected to be conservative.

(2) The remarks made with regard to the turbine inlet temperature of the small engine are also relevant here: A higher pressure ratio causes a higher combustor inlet temperature. On the other hand, the trend to very high temperatures leads to increased wear on the hot section parts and higher maintenance costs, as well as higher initial cost (arising from the need for better materials and turbine cooling arrangements). At present engines of this size have turbine inlet temperatures up to 2800°R while operating at pressure ratios up to 30. The effect of higher maintenance cost was judged to be the dominant influence here instead of the engine size as shown by the continued use of the overbuilt JT4A (despite its fuel penalty as a pure jet) and the trend towards variable thrust take-off (if the runway length and aircraft load permit, less than 100% power is used at take-off so that less stress is put on the engine). This suggests that future engines, while perhaps built to operate at high temperature, will not generally be operated there. For this reason, it is assumed here that while the pressure ratio will rise some, the overall operating temperature will largely remain the same.

(3) The increased pressure ratio permits the bypass ratio to be increased some without degradation of the cruise SFC. However, there are constraints. A very large bypass implies a larger and heavier engine unless the core can be made small enough through higher operating pressure and temperature (more work per pound of air). In any case, an upper limit of 8-10 for the bypass ratio is generally recognized; beyond that point, it is more economical to remove the fan shroud and create a turboprop engine (see segment 3 of this part). As no increase in the turbine inlet temperature (operating temperature) has been assumed, it is more reasonable here to opt for the lower bypass, 8.

The idle SFC is determined in Figure 45 by applying to the rated SFC curve the same ratio (at each rated thrust level) as exists between the rated and idle SFC curves for newly manufactured engines (Figures 6 and 24). It must be recognized that these SFC levels may be a little low in view of the relatively modest turbine inlet temperatures (TIT) involved. While these are representative of today's engines, newly certified ones may be able to attain higher temperatures without undue wear. The advantage of the higher temperatures is that it permits smaller engines to do a given amount of work (more power per mass of air) and thus saves on weight. SFC will generally increase, however.

The SFC line from Figure 45, the technology lines from Figures 43 and 44, and the approximation for EPAP given in equation (2) allow calculation of the HC and CO EPAPs expected to be realized for newly certified engines. These EPAPs are shown on Figures 46 and 47. Implicit in this calculation is the assumption that the idle pressure ratios of the two sample NCEs are the same fraction of the rated pressure ratios as is found in existing engines (6% idle assumed). This assumption leads to idle pressure ratios of 3.0 and 6.0 respectively for the two hypothetical engines above. It should be cautioned, however, that this EPAP computation procedure involves some extrapolation for the technology lines of Figures 43 and 44 as they are based upon data only up to IPR ≃ 4.0 whereas the larger hypothetical engine has an IPR of 6.0.

As indicated earlier, the control of NOx emissions is expected to be achieved through use of the category 3 technology. The NOx control performance of these techniques (as typified here by the NASA/GE double annular combustor) and for that matter, any combustor, is sensitive to the operating pressure and temperature. As the combustors of new engines will be run at considerably different operating conditions from that of the CF6-50C for which the double annular combustor performance is known, it is necessary to adjust the EI data to that which would be expected in the hypothetical newly certified engines. This could be done by referral to a modified Lipfert type chart wherein category 3 technology data have been correlated against P_3 (combustor pressure). However, the concern about the validity of such a simple correlation which was discussed in parts B and C is equally valid here, and perhaps more so, in light of the extrapolation of conditions involved. Hence, the NOx correction formula from the NASA ECCP (reference 59) will be utilized although even its application involves extrapolation. Its primary advantage is that it represents a semi-empirical multivariate correlation taking into account several physical mechanisms of NOx production. Appendix E explains the calculation procedure.

Inasmuch as the demonstrated technology upon which this projection is based comes from the 50,000 lb. thrust class CF6-50C engines, an important assumption in this analysis is that some sort of advanced combustion system will be available to the small T1 class engines that offers low NOx performance comparable to the double annular combustor. Such an advanced combustor might evolve from the piloted premix/prevaporization system being investigated for T1 class engines in NASA's Pollution Reduction Technology Program (Reference 34). It is necessary to make this assumption because the double annular system is likely to have a very high surface to volume (S/V) ratio in small sizes (which would probably destroy the HC and CO gains made through application of various control schemes - see Figure 17) and is thus probably not well suited to application in small engines. Application of the CF6-50C double annular emissions data as corrected and combined with the modal fuel flow rates leads to the NCE technology curve shown on Figure 48 (computation in Appendix E).

In summary, it is evident that the NCEs can be very clean with respect to HC and CO emissions and reasonably clean in NOx emissions although apparently the presently promulgated number (EPAP = 3.0) cannot be met with the category 3 technology demonstrated to date. If the NCE cycles do have higher turbine inlet temperatures than postulated, the projected NOx emissions will definitely rise because both the SFC and the EI levels will increase.

3. P2 Standards

There has been considerable discussion recently (References 61, 62, 63, 64) that suggests that turboprop propulsion may again find utility in large, long haul air transports because of the excellent fuel economy afforded. Such fuel efficient designs are becoming more attractive despite drawbacks (i.e., propeller maintenance) because of the ever rising cost of fuel.

A commonly discussed concept is the "propfan" engine designed for cruise speeds approaching that of current subsonic jet transports (Mach 0.78 vs. 0.82). This engine represents the transition between a true fan engine (with numerous shrouded blades) and a true propeller engine (with a few unshrouded blades). The choice of one system or the other is basically a choice of the optimum thermodynamic cycle which in turn determines the SFC. The optimum cycle is very sensitive to both takeoff power requirements and the selected speed and thrust requirements at cruise. The trend for jets over the last two decades has been towards larger and larger bypass ratios (initially bypasses of 0, now typically 5-6 and 8-10 proposed) in order to improve the thermodynamic cycle and hence the SFC. The propfan is merely a continuation of this trend (bypass, 12-25) for which the bypass has reached the point that the weight of the surrounding shroud is excessive and hence has been removed, producing instead a low bypass, highly loaded propeller for high subsonic speeds (a typical low cruise speed propeller is lightly loaded in terms of work done per unit of air and has a bypass of 50 to 100).

In view of the possible development and extensive deployment of this type of turboprop, it appears possible that the EPA may find it necessary to take measures to ensure that the emissions technology of such an engine be compatible with competing engines (principally newly certified T2 class engines).

The technology that would be available to these engines is the same as that which will be available to newly certified T2 class engines (as summarized in Figures 43 and 44 for HC and CO, and in reference 59 for NOx). In fact, it is conceivable that the same basic gas generator may be used in both applications with either a fan or a propeller/gear reduction apparatus attached. The emissions performance of the combustor, however, will differ between applications in the two classes because of different operating conditions in each mode in the two cases, primarily at idle wherein the turboprop is likely to run at a higher speed and hence possess lower emissions of HC and CO, but higher emissions of NOx, from the combustor than it would experience in a turbofan application.

To project the EPAP values for the advanced large turboprop (propfan) it is necessary to estimate the power specific fuel consumption (PSFC) and the combustor operating conditions. The former is necessary because equation (1) requires SFC values for calculation of EPAP.* The latter is necessary in order to project the EI values for the pollutants when the combustor operating environment differs from that for which the values are currently known or estimated.

To estimate the SFC, it is necessary to know the thermodynamic cycle of the engine. Two cycles were postulated for this, one representing a smaller engine, the other a large engine. The cycles, given below in Table III-6, are compatible with those selected to represent newly certified T2 class engines.

Table III-6

Power	5,000 HP	50,000 HP
Bypass Ratio* (β)	12,25	12,25
Pressure Ratio	20.0	40.0
Turbine Inlet Temperature	2680°R	2860°F

* This is a measure of the propeller size and as such is characteristic of the conversion of power to thrust. This is, therefore, not required to estimate PSFC, but is useful in establishing core size (M_{air}) comparisons between P2 and T2 engines of the same thrust.

From these points, the PSFC curve shown on Figure 49 established. That curve is essentially independent of the particular bypass ratio (propeller size) selected as mentioned in the footnote to the table.

The engine sizes were selected by the following consideration. The T1 class (general aviation) and the T2 class (commercial) are separated at the 8000 pound thrust mark. With a few exceptions (eg., the 6,500 lb.-thrust M45H in commercial service and the 11,400 lb.-thrust Spey Mk 511 on a business jet), this offers a clean distinction. Depending upon the propeller selected (corresponding to a bypass of 12 to 25), 8000 pounds of thrust corresponds to 4100 horsepower on the low end and 5800 horsepower on the high end. It is reasonable then to select 5000 horsepower as the lower limit of the P2 class which may be utilized for advanced commercial application. For comparison, the largest P2 class engine now in use in the U.S. is the Allison 501 with a 4700 horsepower rating.

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*Note that for the P2 class, the power SFC in units of pounds of fuel per hour horsepower is selected rather than the thrust SFC in units of pounds of fuel per hour per pound of thrust as is the case for the T1-T2 classes; this reflects the difference in the definitions of EPAP between the classes specified in the regulations.

Utilizing the combustor technology information from Figures 43 and 44 and in reference 59 along with the fuel consumption performance in Figure 49, technology lines for HC, CO, and NOx were made. The computation is presented in Appendix F and the results shown in Figures 50, 51, and 52. The calculation for the HC technology line resulted in very low EPAP values similar to those recorded by the technology line for T2 class newly certified engines (Figure 53). That is consistent with the fact that (1) for a propfan type of propeller, the thrust to power ratio at the rated condition is of the order one (eg., EPA estimates for a $\beta = 12$ propeller the thrust to power ratio would be about 1.4) and (2) the two classes of engines are utilizing the same combustor technology, albeit under slightly different operating conditions at idle. The CO calculation shows a fairly level curve (EPAP goes from 2.9 to 3.6 over a range of 45,000 horsepower). NOx increases for the larger engines are due to the increasingly severe combustor environment which outweighs the meager SFC improvements seen in the larger engines.

HC EPAP AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

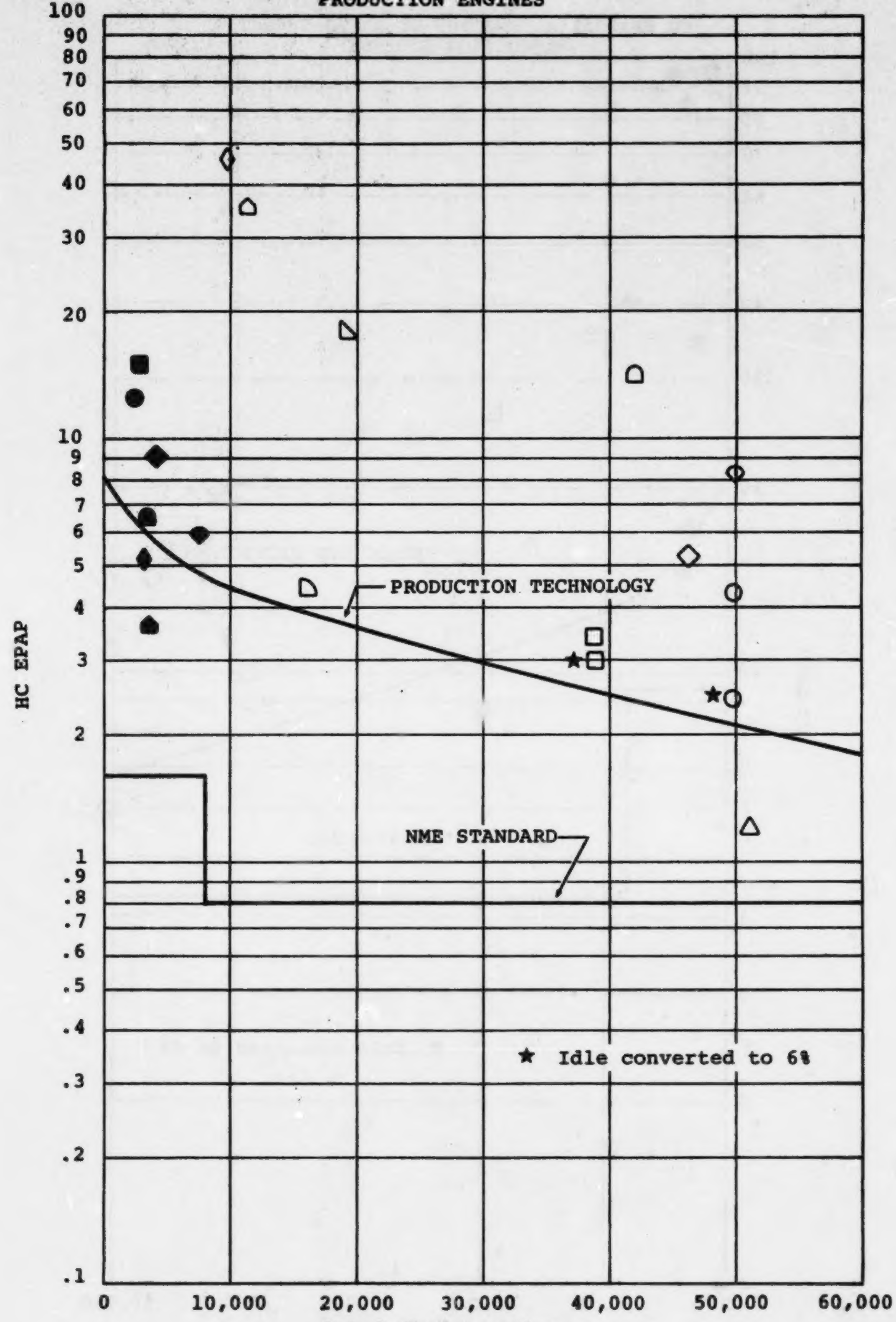


Figure 3

CO EPAP AS A FUNCTION OF RATED THRUST PRODUCTION ENGINES

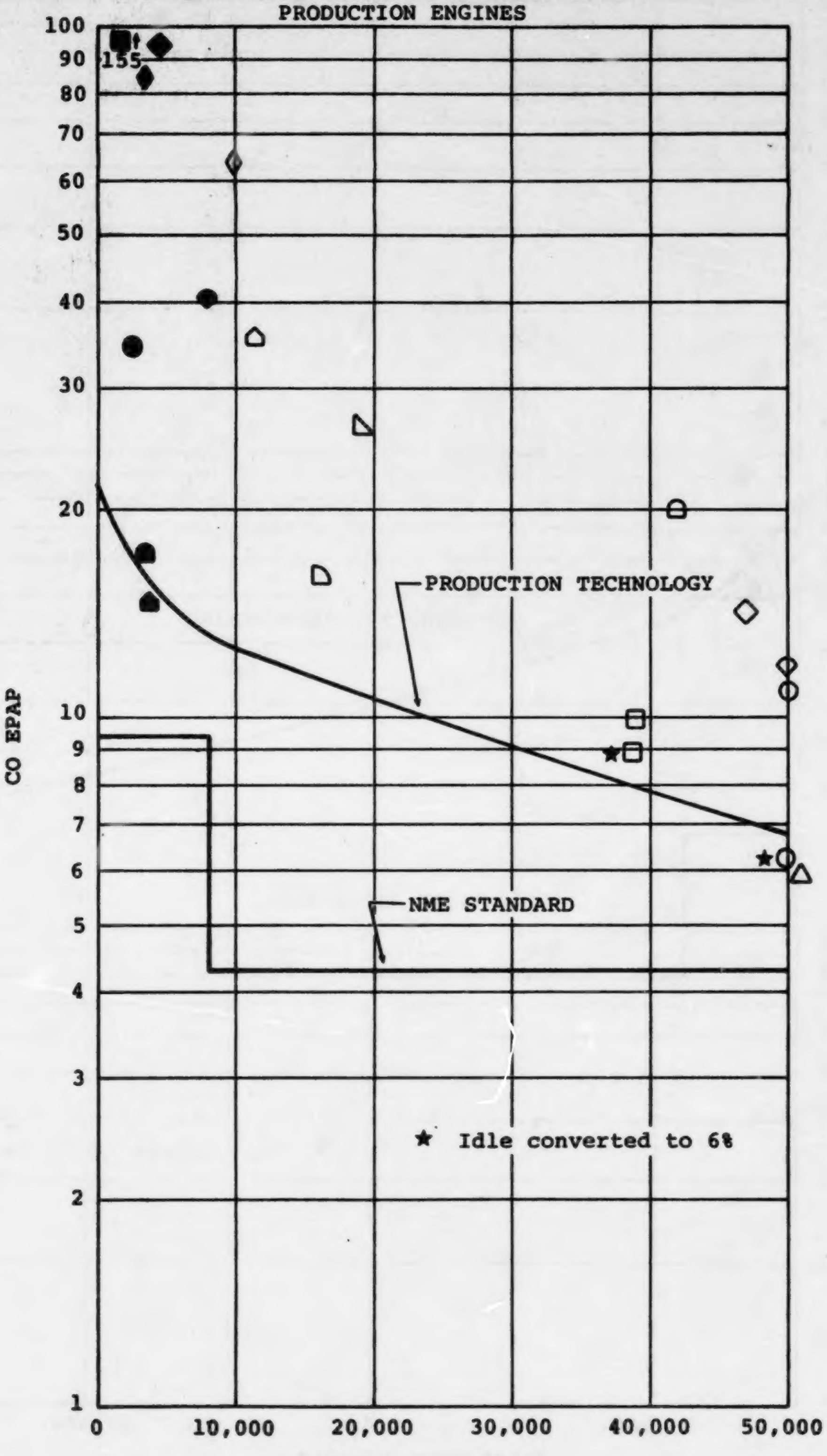


Figure 4

NOx EPAP AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

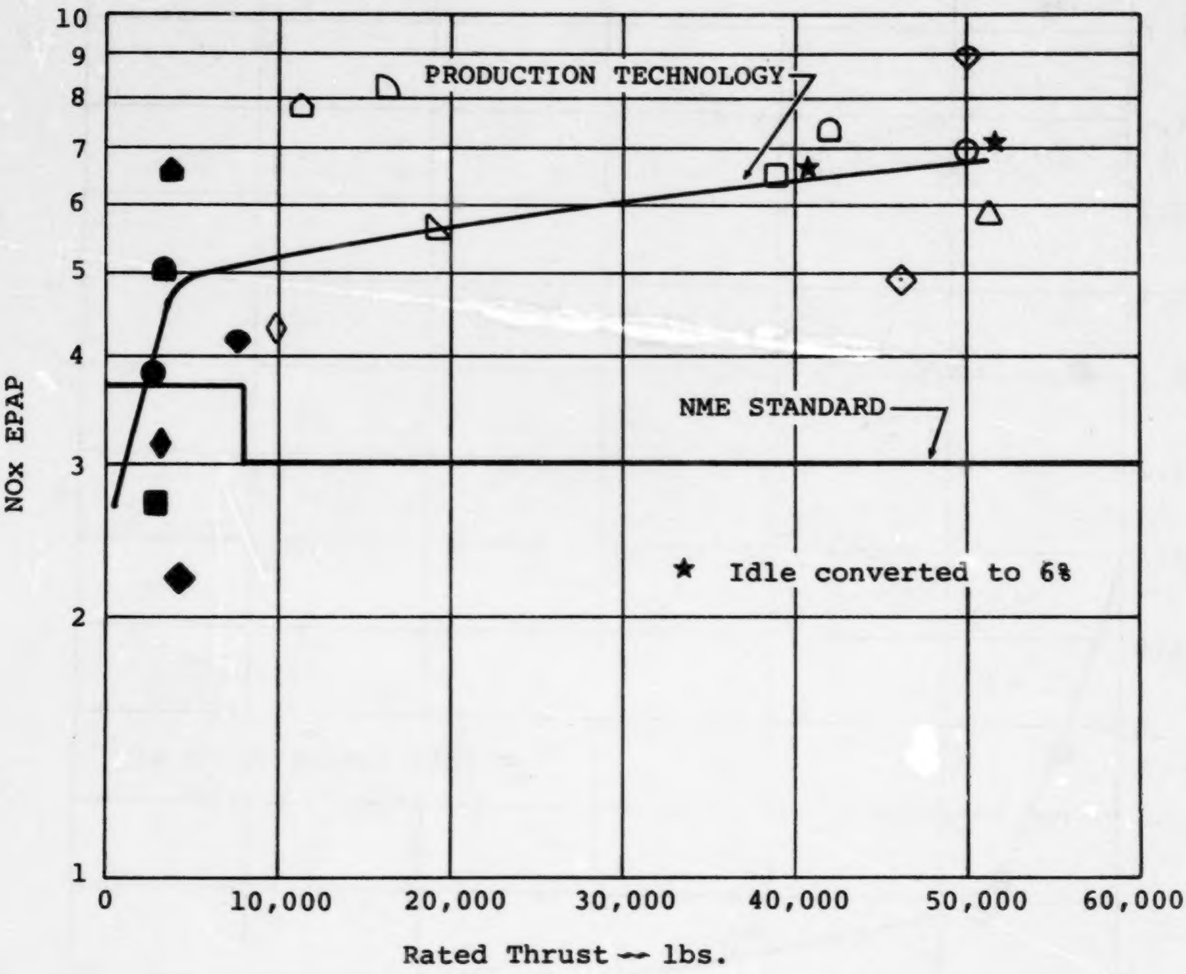


Figure 5

IDLE TSFC AS A FUNCTION OF RATED THRUST
PRODUCTION ENGINES

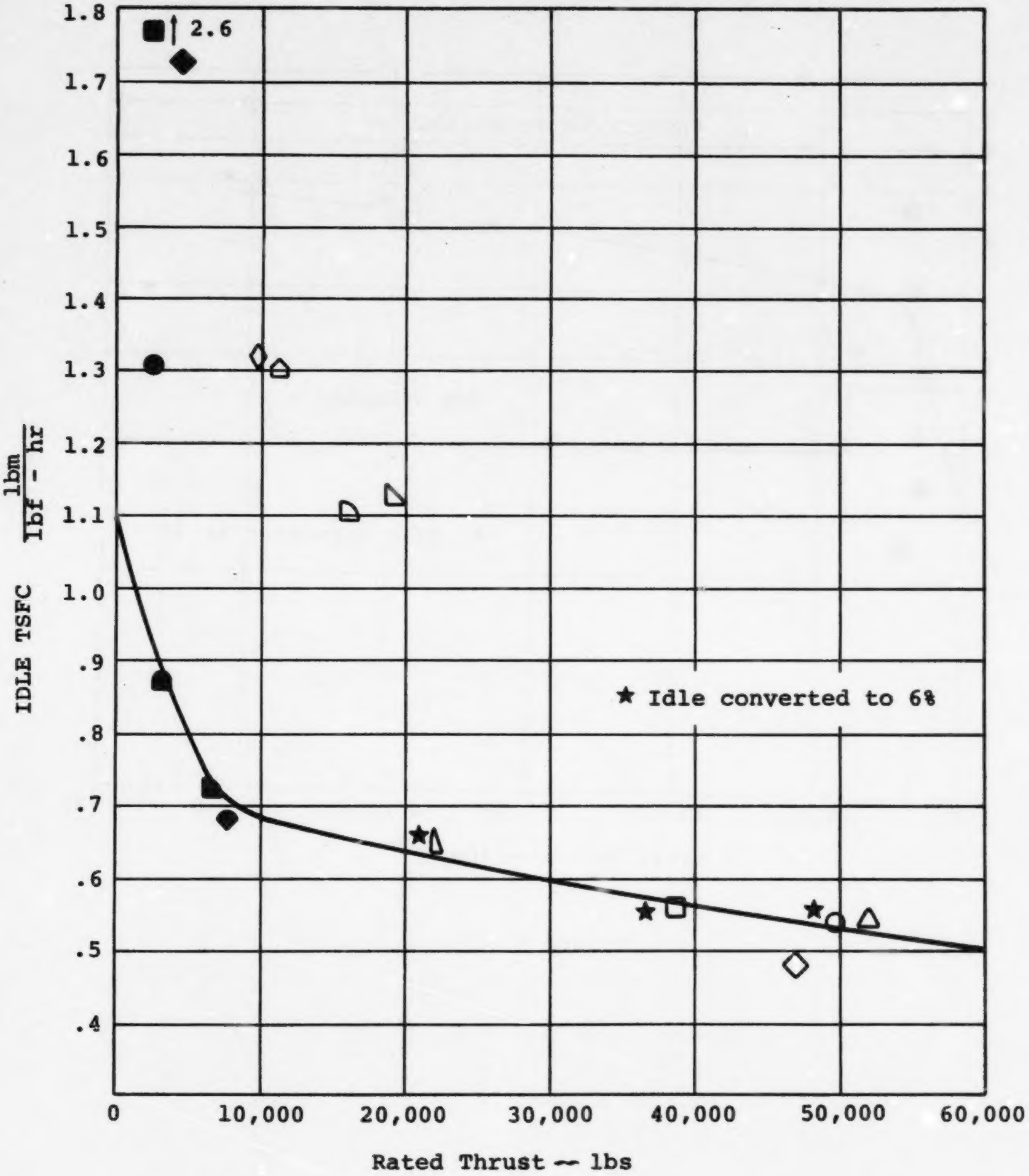


Figure 6

IDLE SFC AS A FUNCTION OF BYPASS RATIO

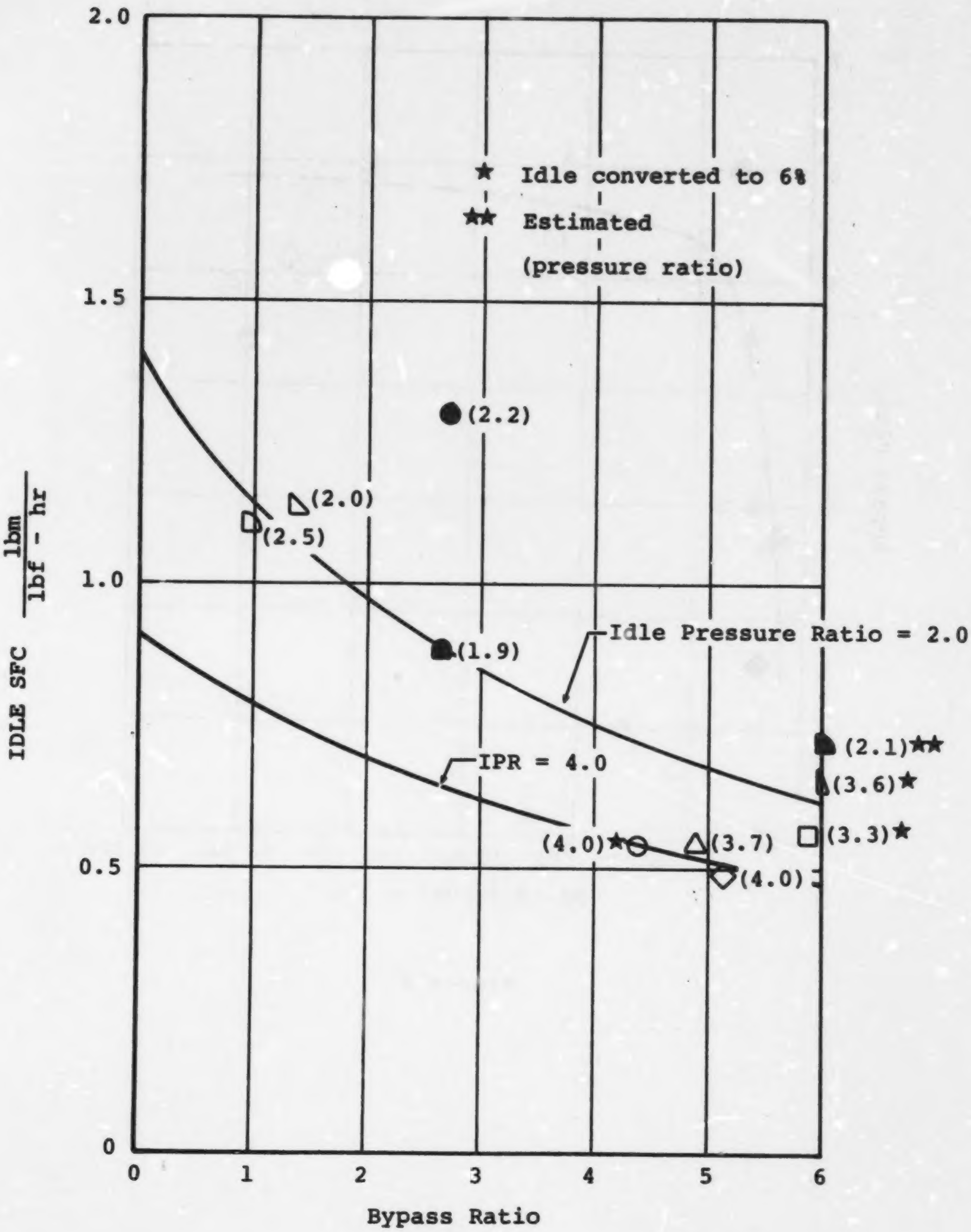


Figure 7

BYPASS RATIO AS A FUNCTION OF RATED THRUST

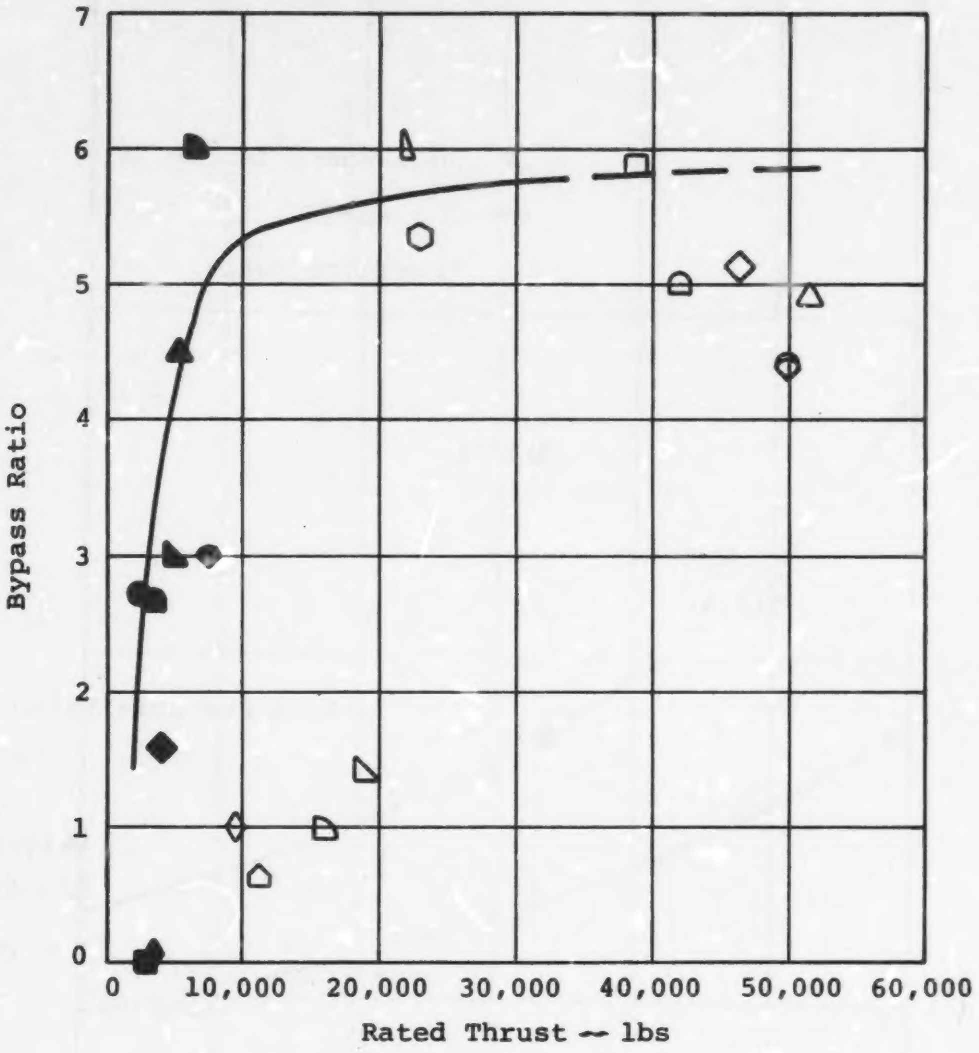


Figure 8

IDLE PRESSURE RATIO AS A FUNCTION OF RATED THRUST

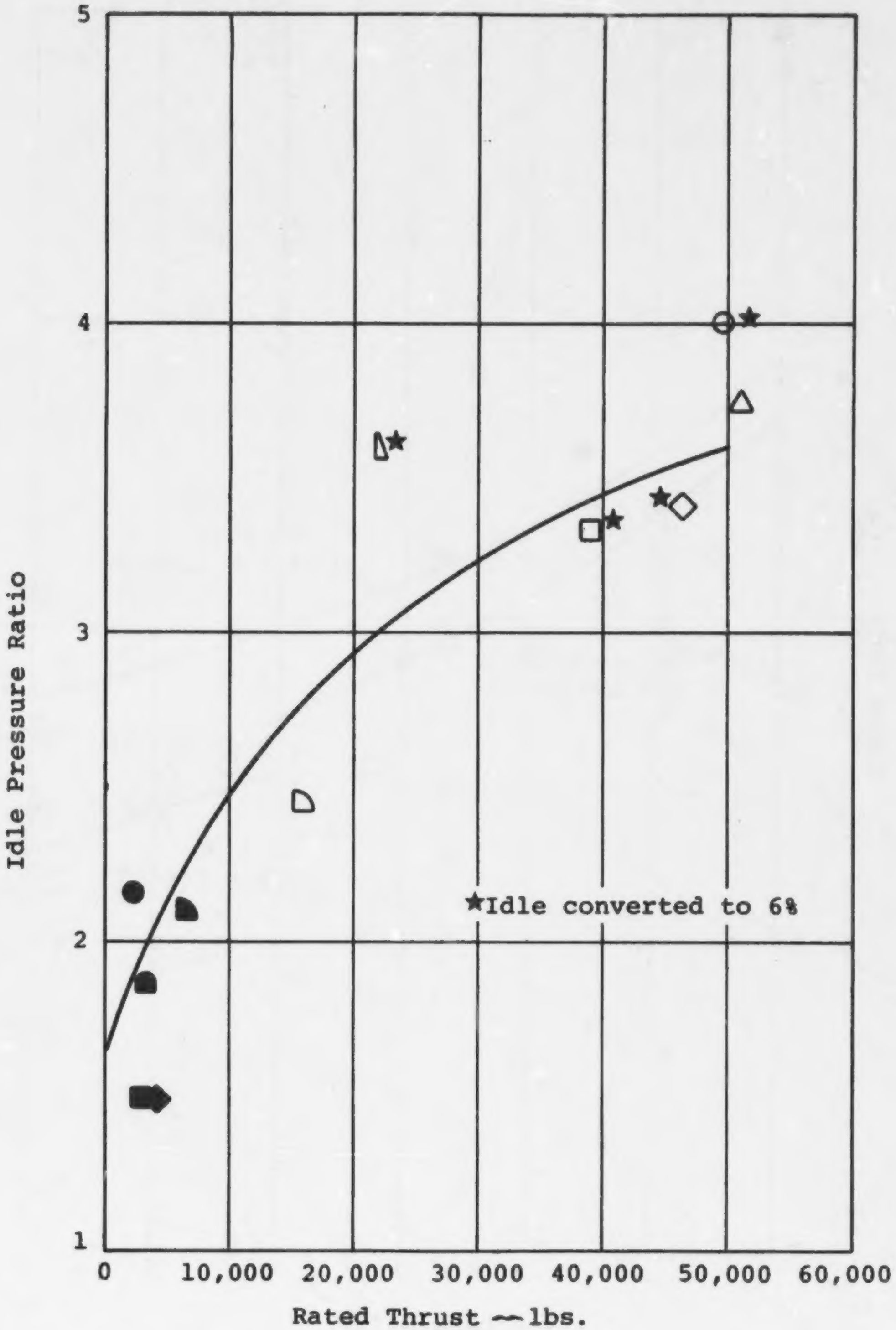


Figure 9

RATED TSFC AS A FUNCTION OF BYPASS RATIO

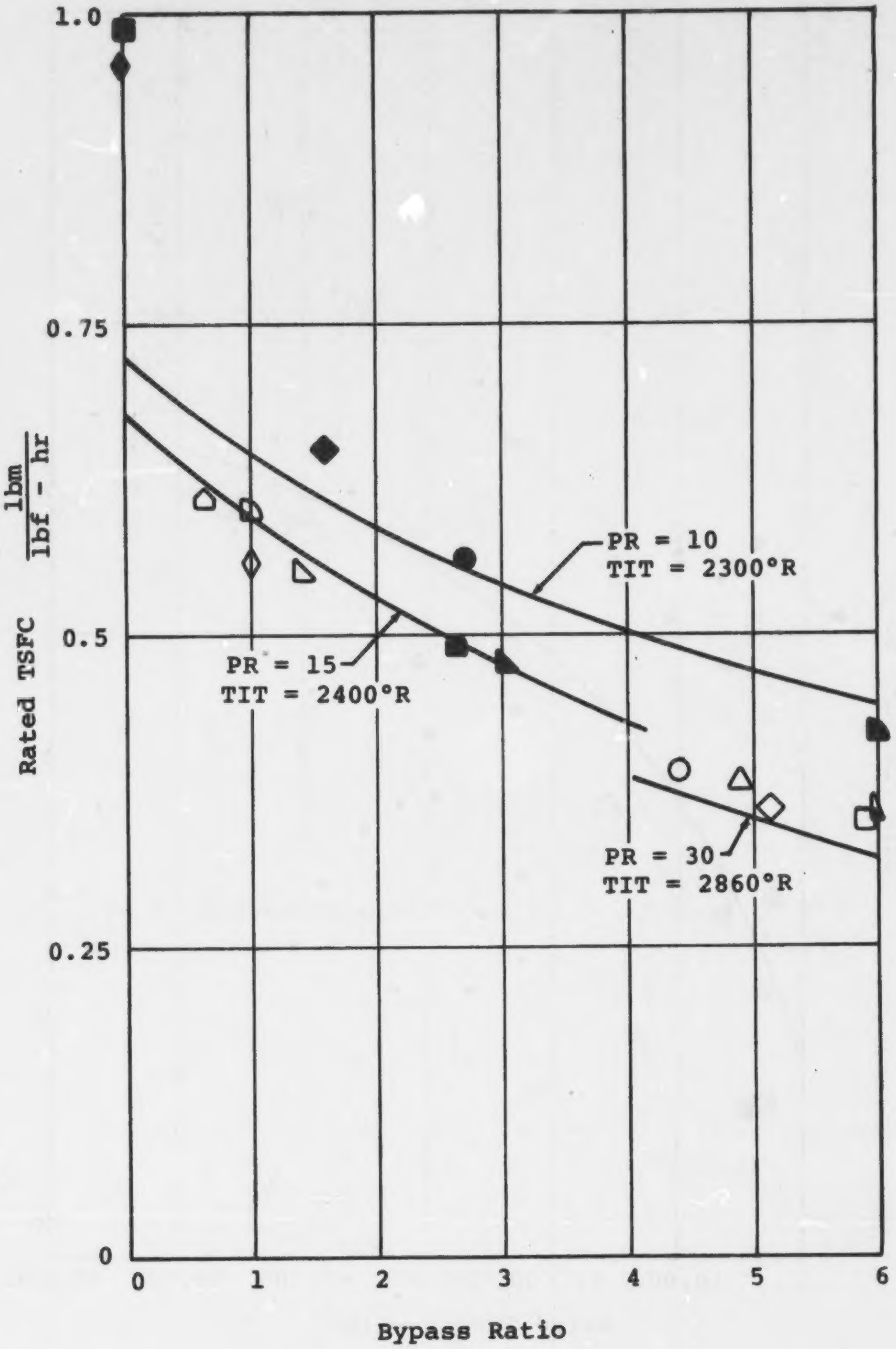


Figure 10

BYPASS RATIO AS A FUNCTION OF RATED PRESSURE RATIO

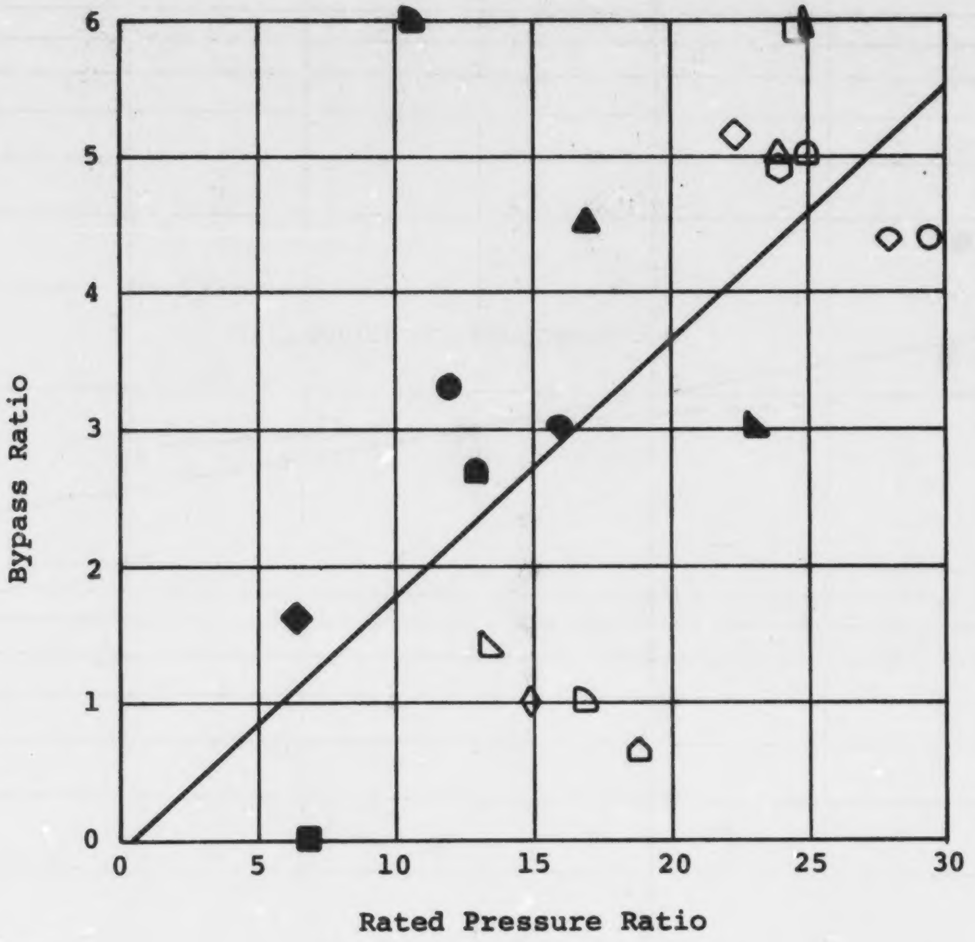


Figure 11

HC EMISSION INDEX AT IDLE AS A FUNCTION OF RATED THRUST PRODUCTION ENGINES

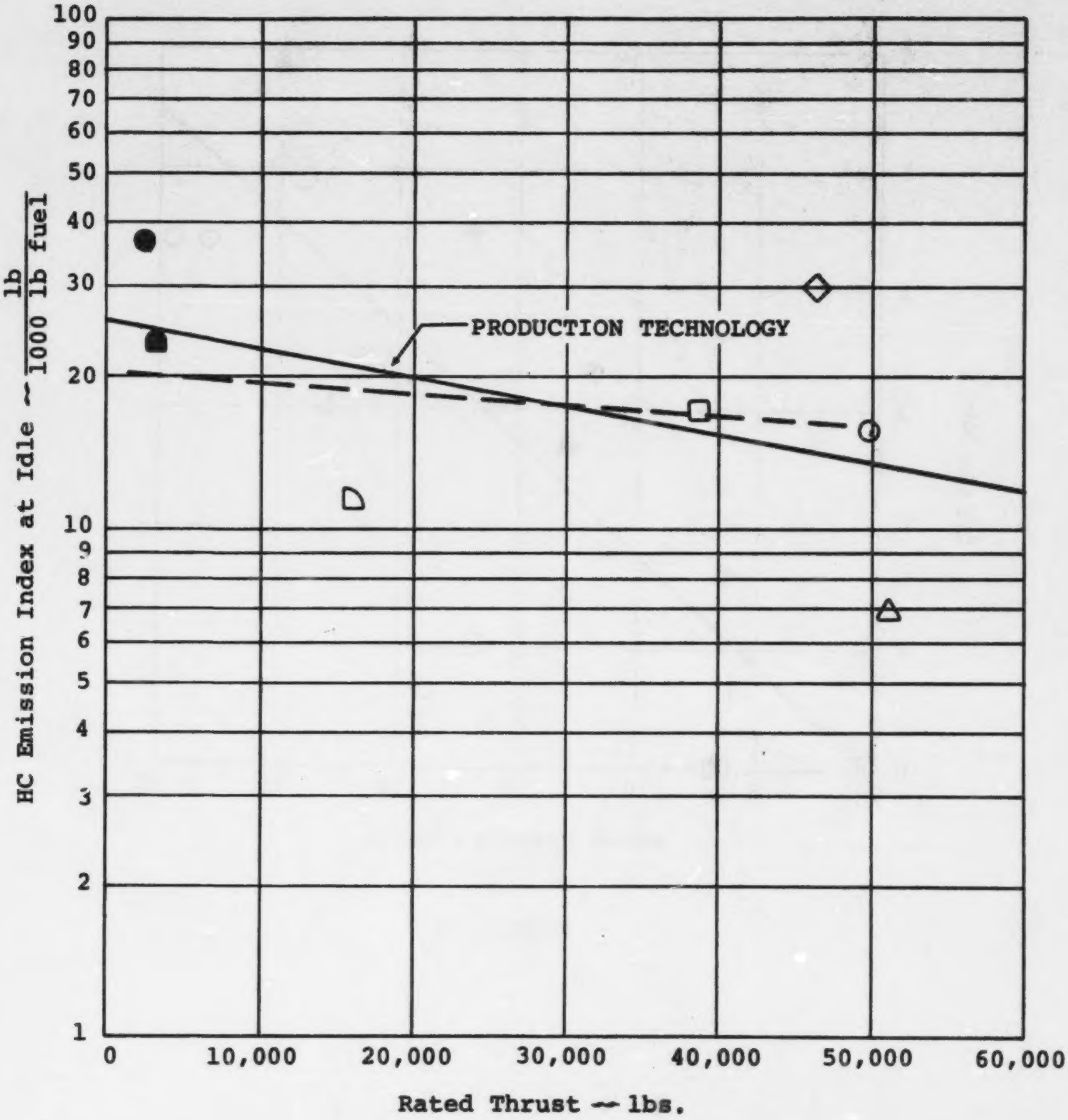


Figure 12

CO EMISSION INDEX AT IDLE AS A FUNCTION OF RATED THRUST PRODUCTION ENGINES

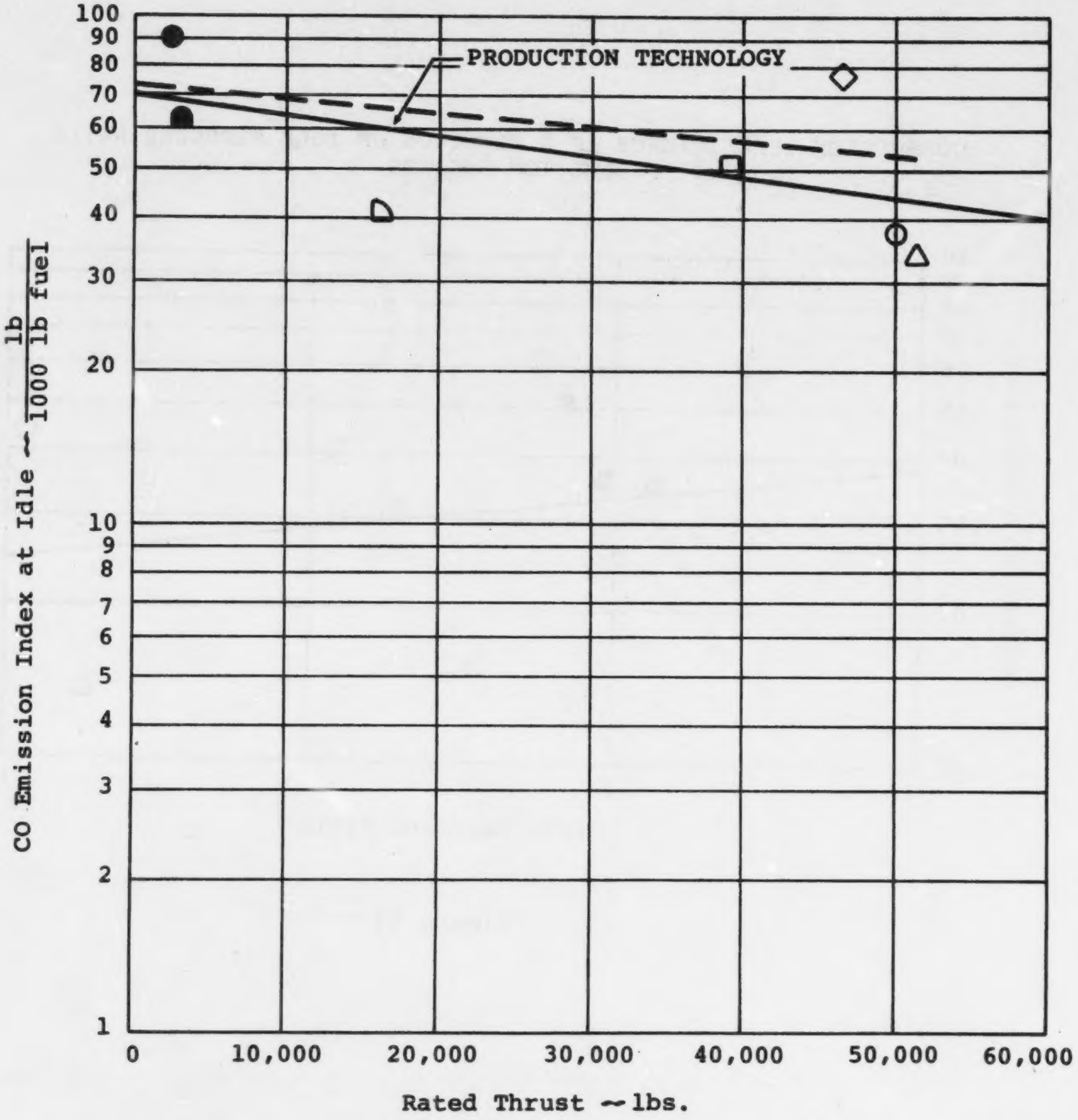


Figure 13

COMBUSTION INEFFICIENCY AS A FUNCTION OF IDLE PRESSURE RATIO PRODUCTION ENGINES

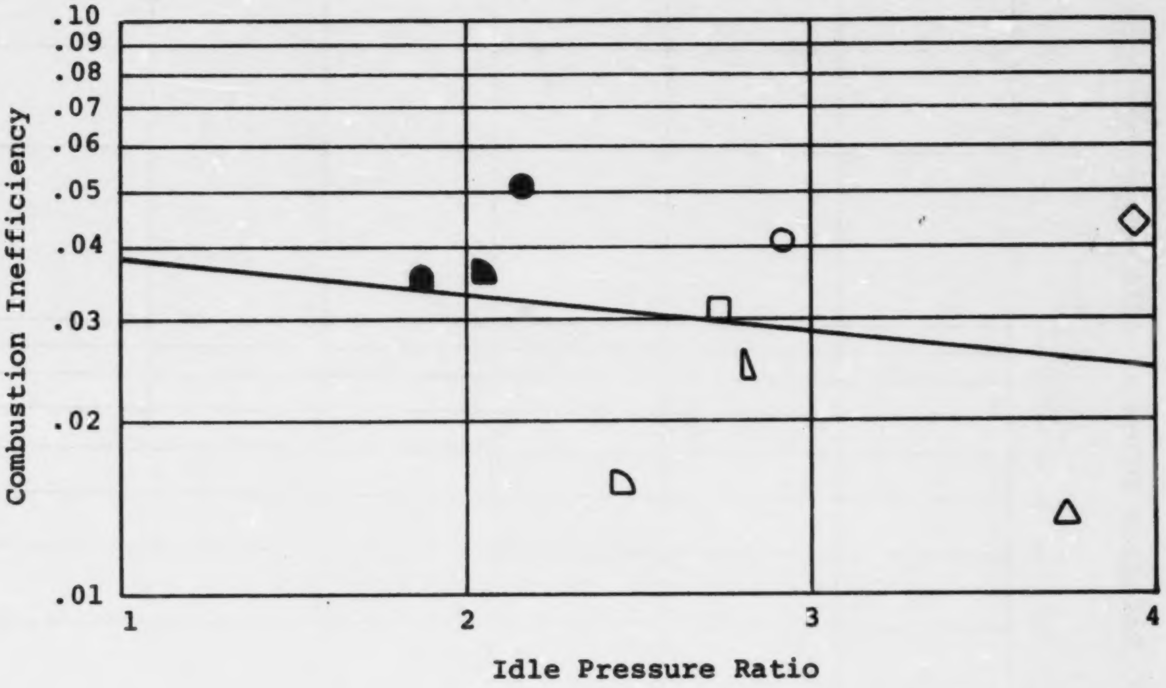


Figure 14

HC EMISSIONS INDEX AT IDLE AS A FUNCTION OF IDLE PRESSURE RATIO
PRODUCTION ENGINES

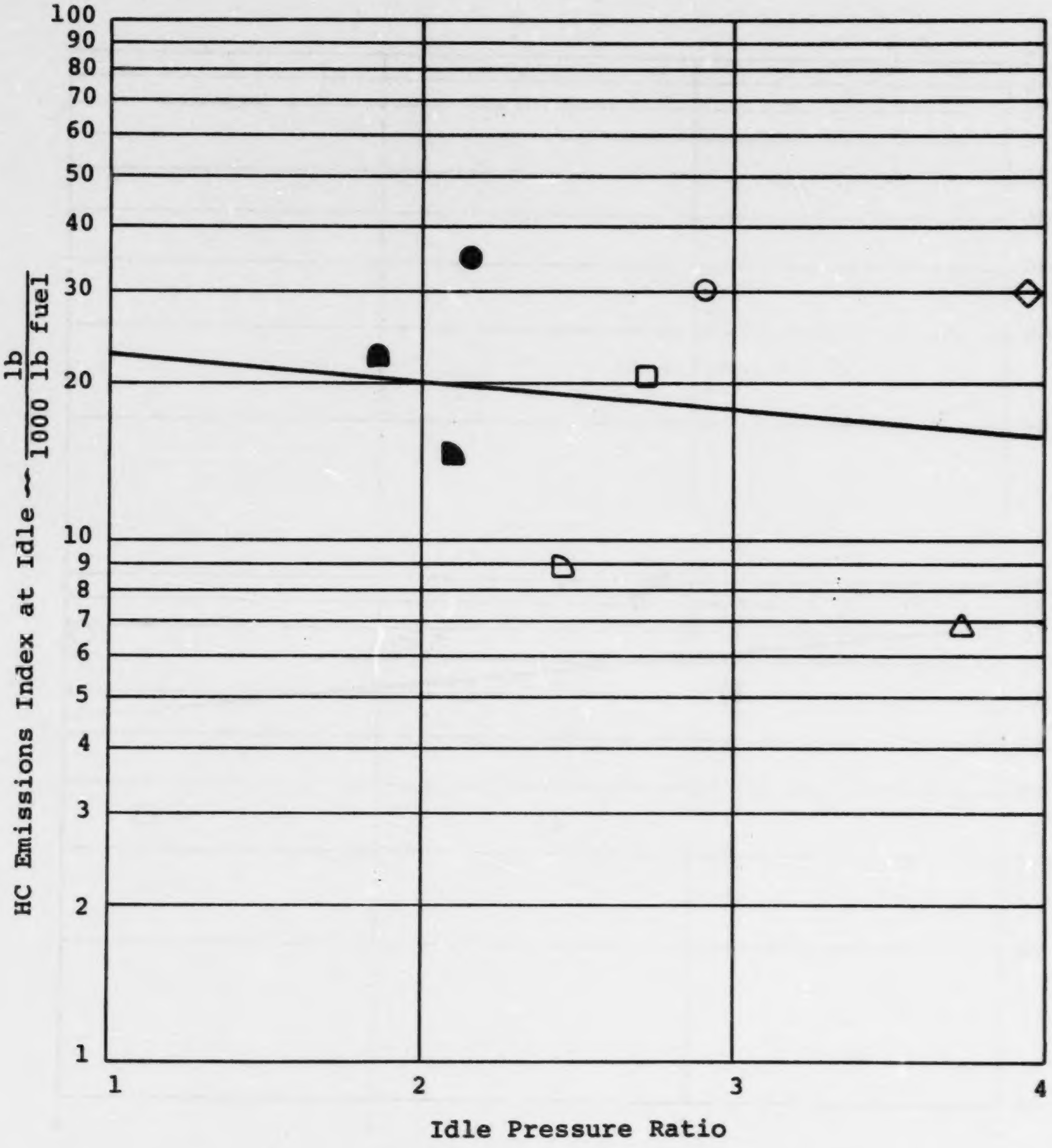


Figure 15

CO EMISSIONS INDEX AT IDLE AS A FUNCTION OF IDLE PRESSURE RATIO PRODUCTION ENGINES

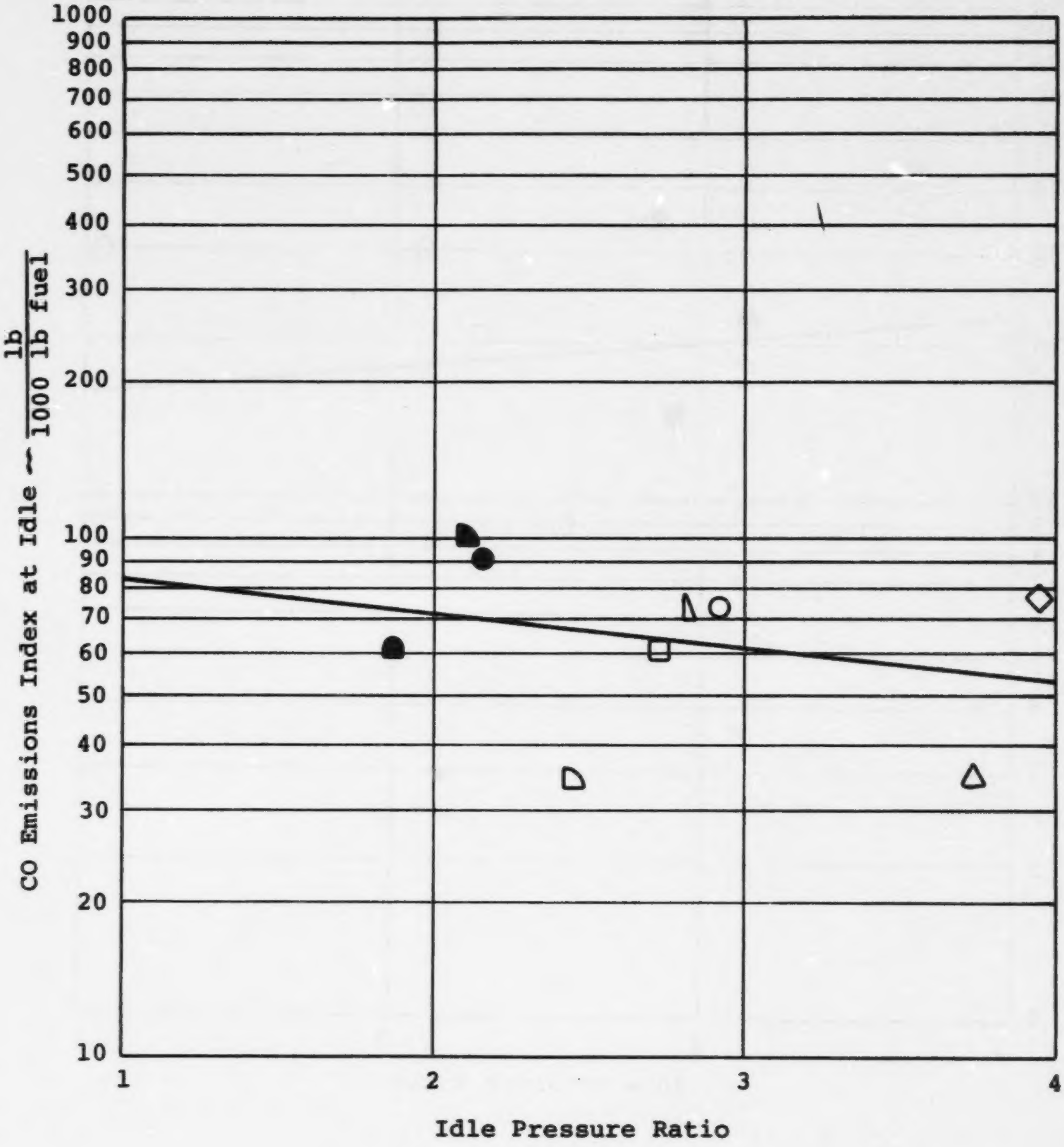


Figure 16

COMBUSTION INEFFICIENCY AS A FUNCTION OF SURFACE TO VOLUME RATIO PRODUCTION ENGINES

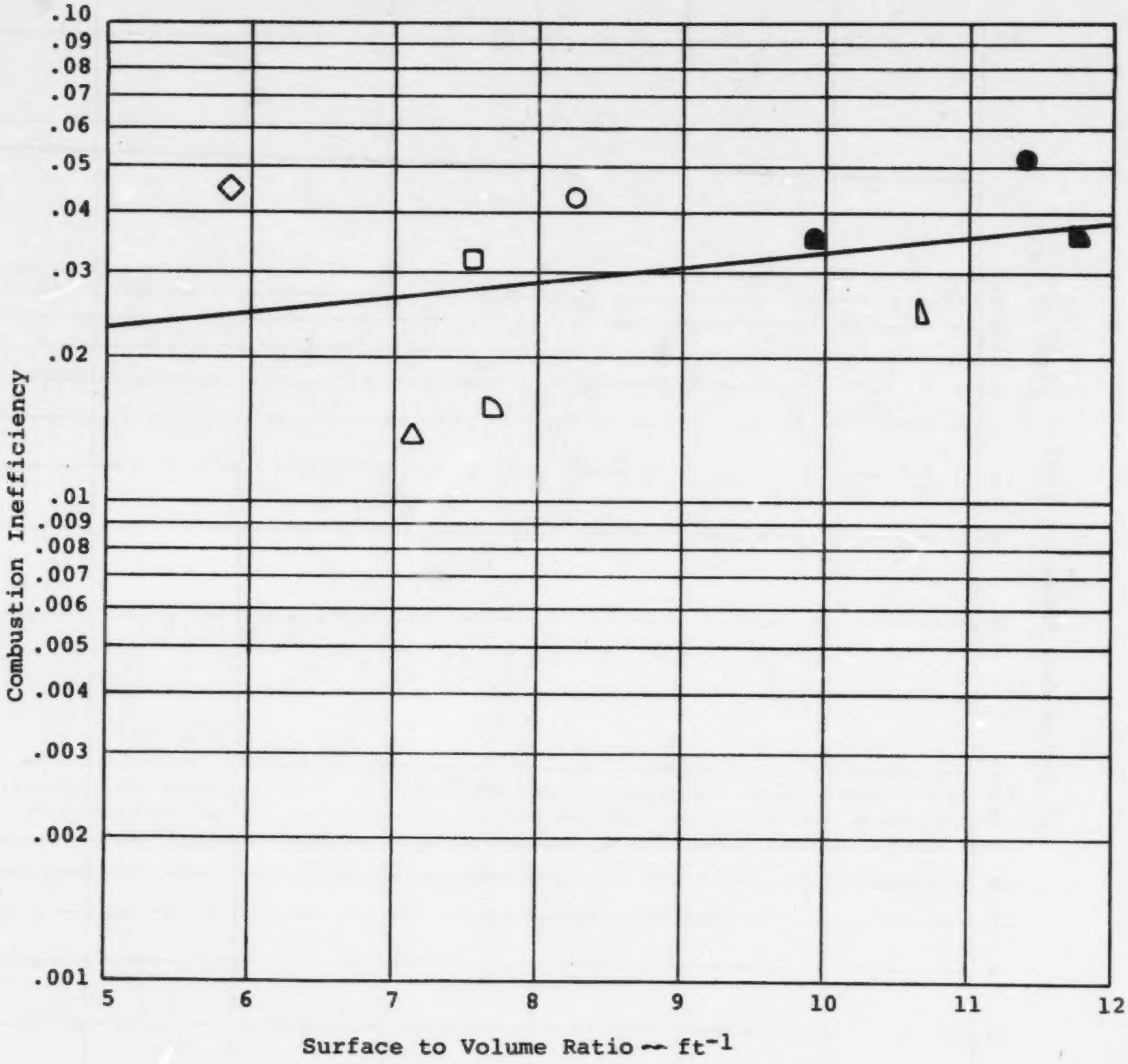


Figure 17

HC EMISSIONS INDEX AT IDLE AS A FUNCTION OF SURFACE TO VOLUME RATIO PRODUCTION ENGINES

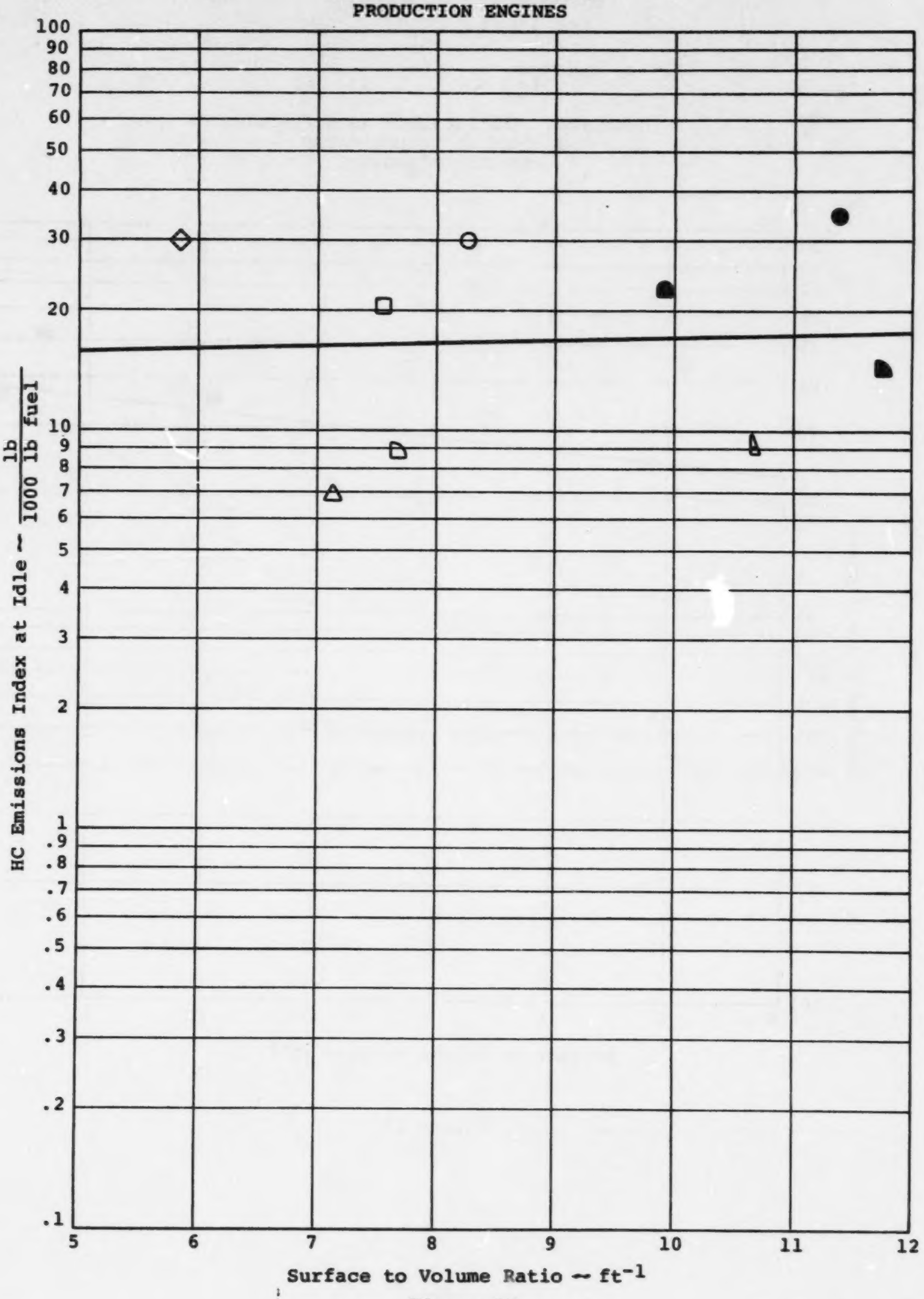
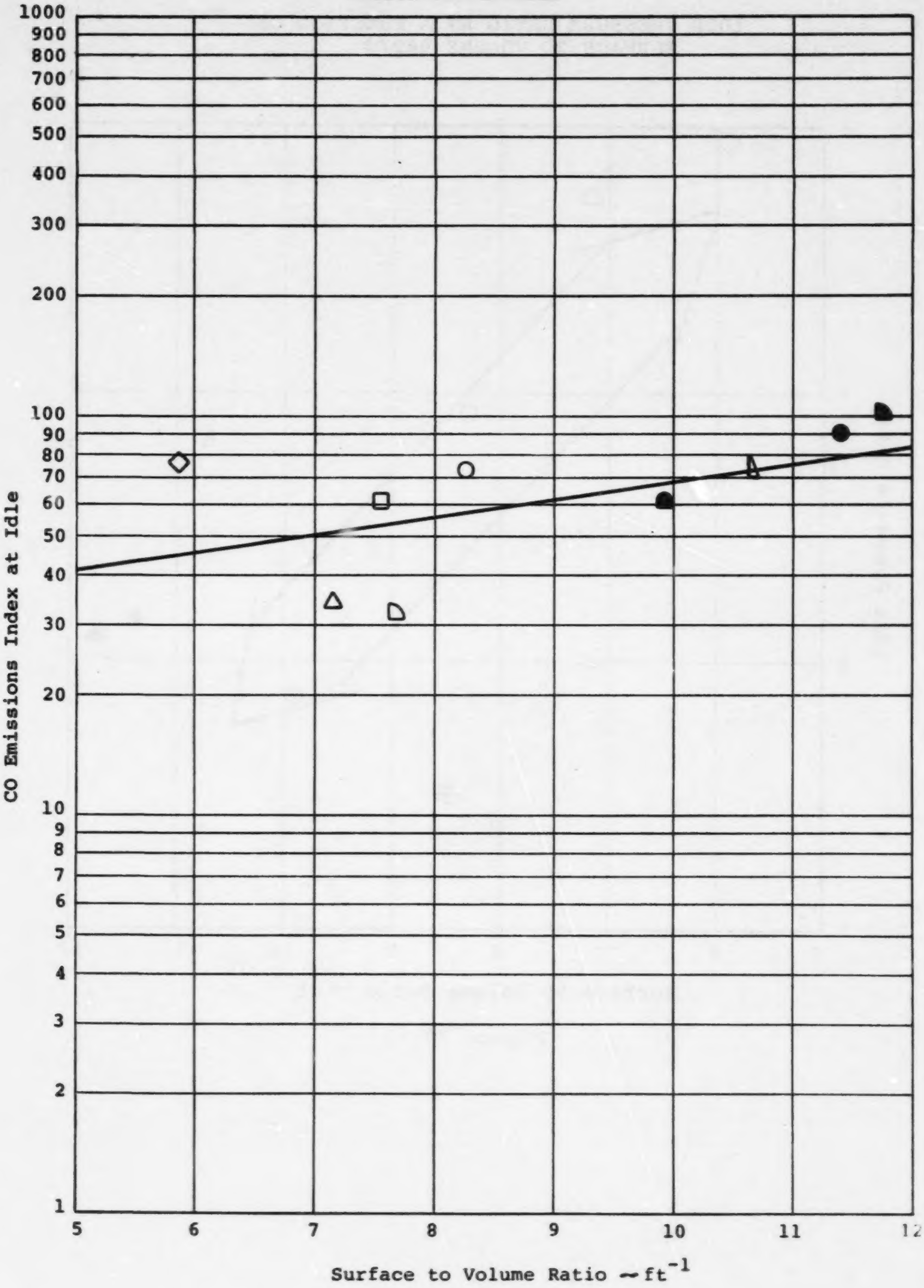


Figure 18

CO EMISSIONS INDEX AT IDLE AS A FUNCTION OF SURFACE TO VOLUME RATIO PRODUCTION ENGINES



Surface to Volume Ratio — ft^{-1}

Figure 19

IDLE PRESSURE RATIO AS A FUNCTION OF SURFACE TO VOLUME RATIO

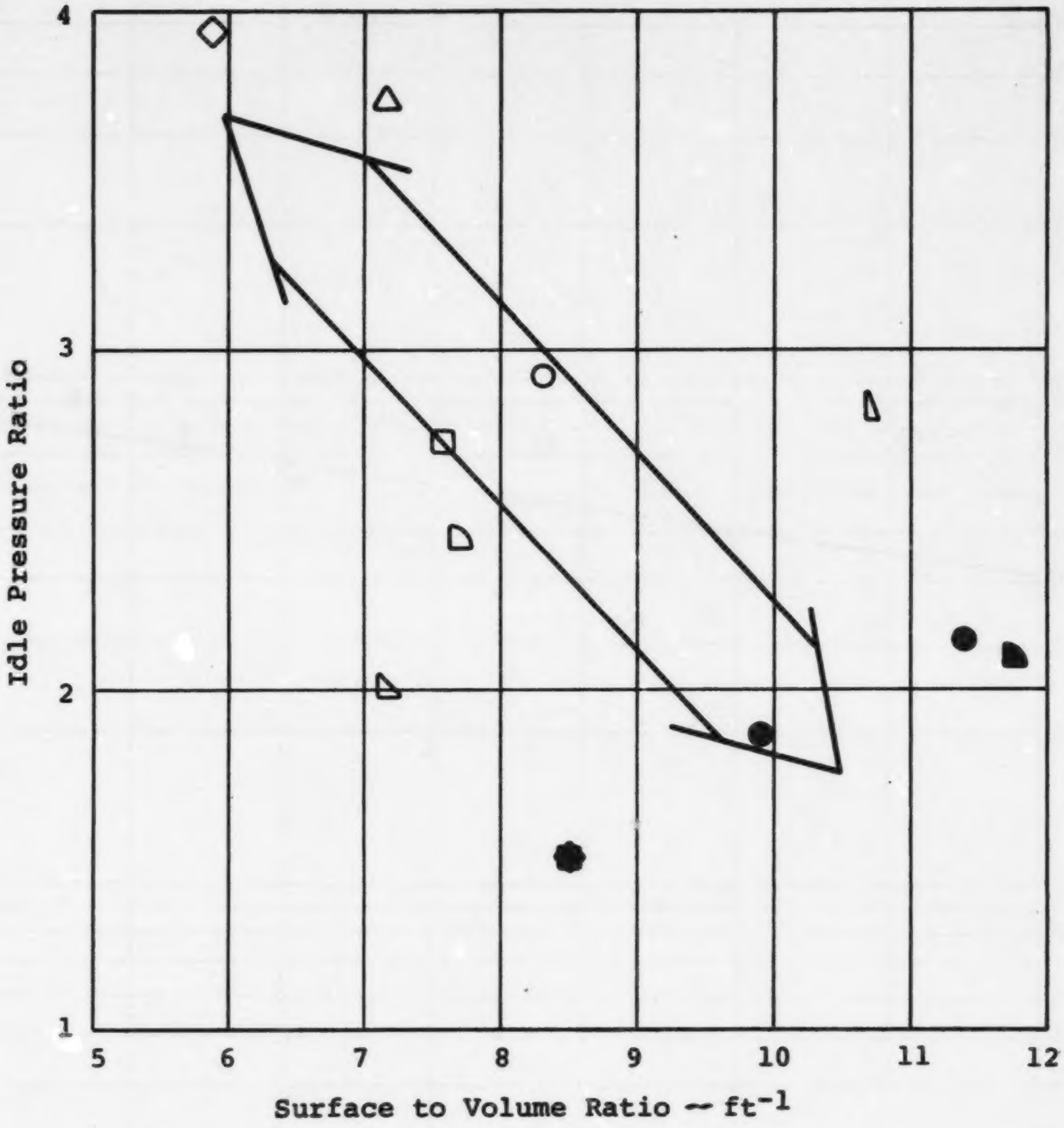


Figure 20

COMBUSTION INEFFICIENCY AS A FUNCTION OF AIR LOADING PARAMETER PRODUCTION ENGINES

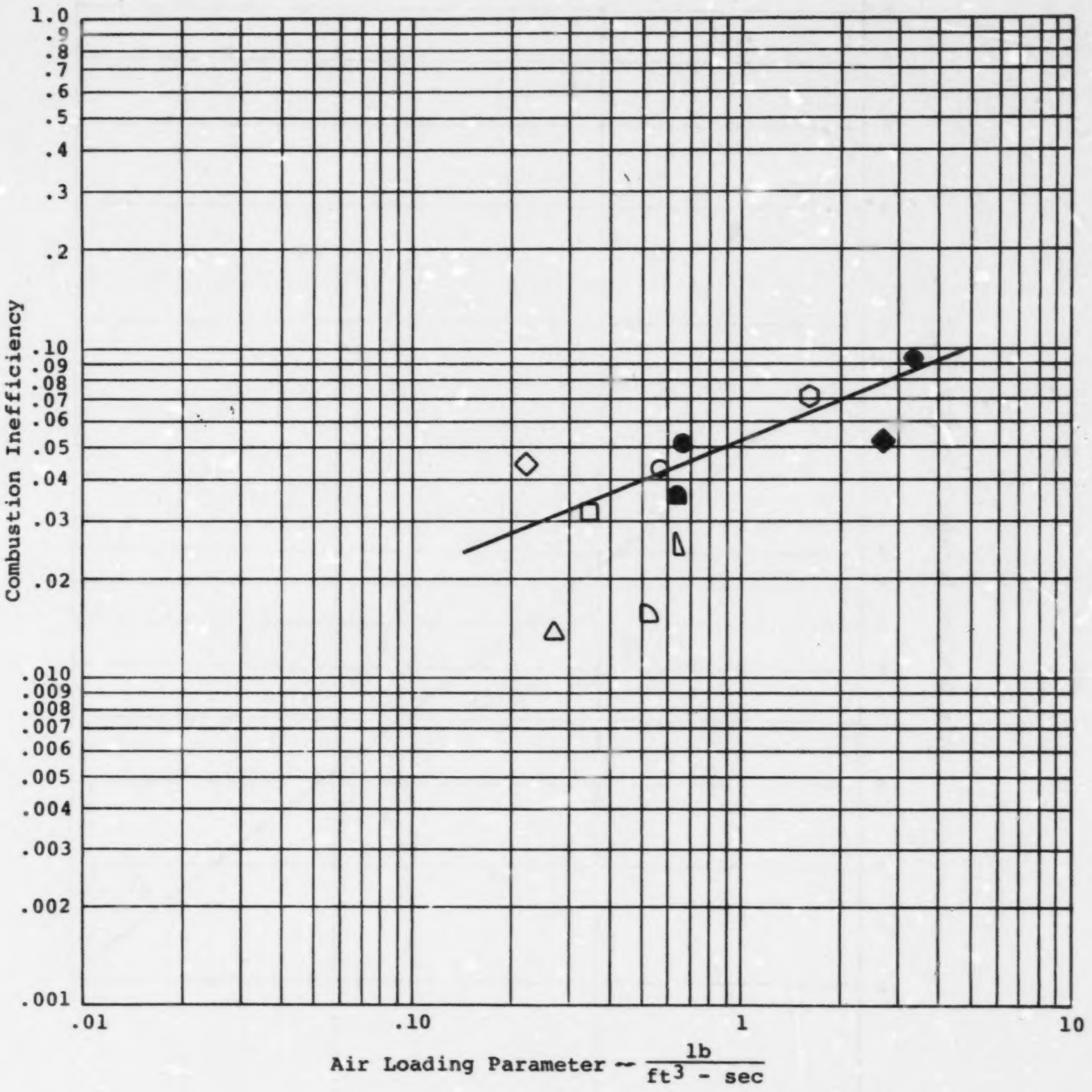
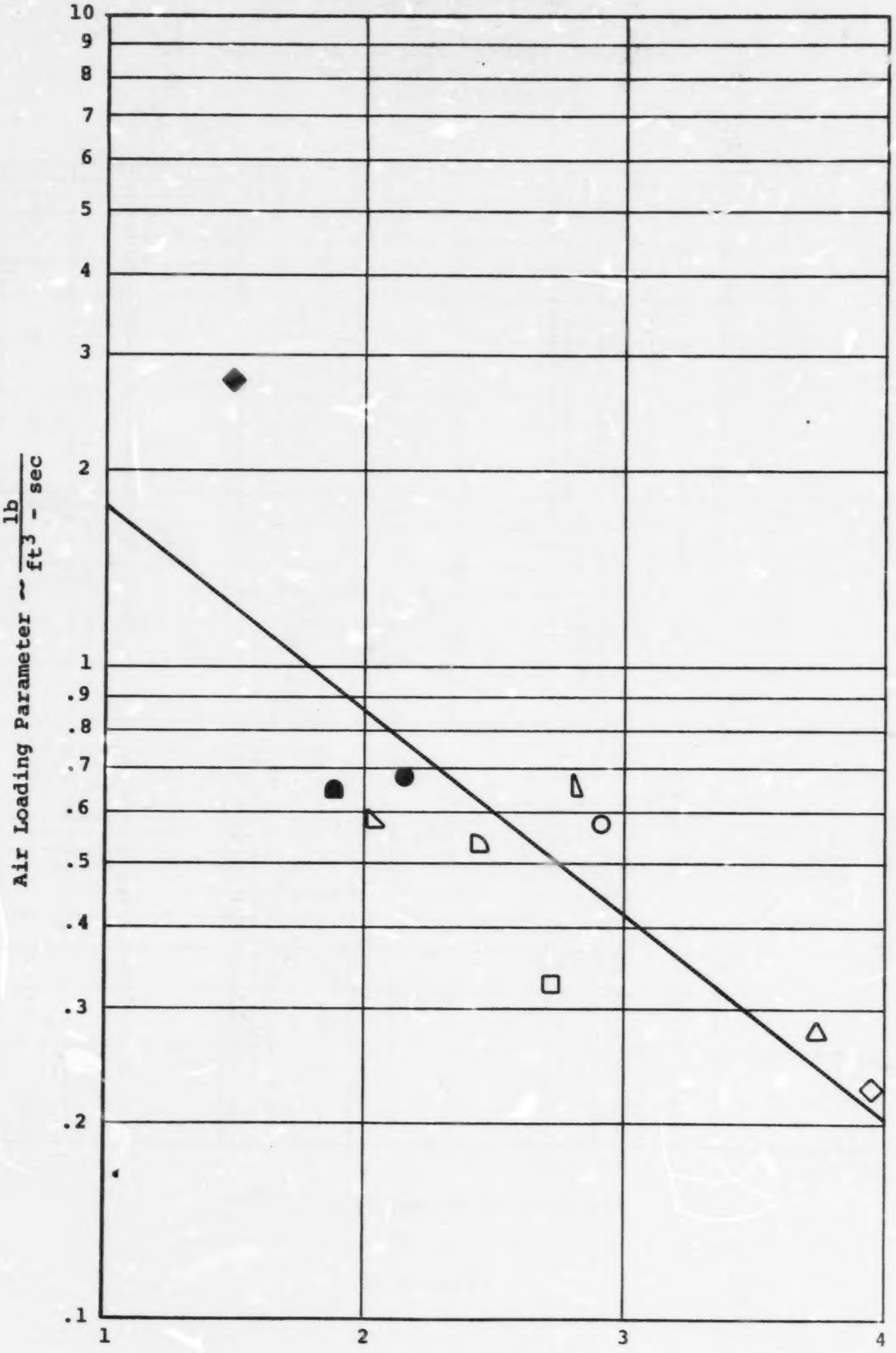


Figure 21

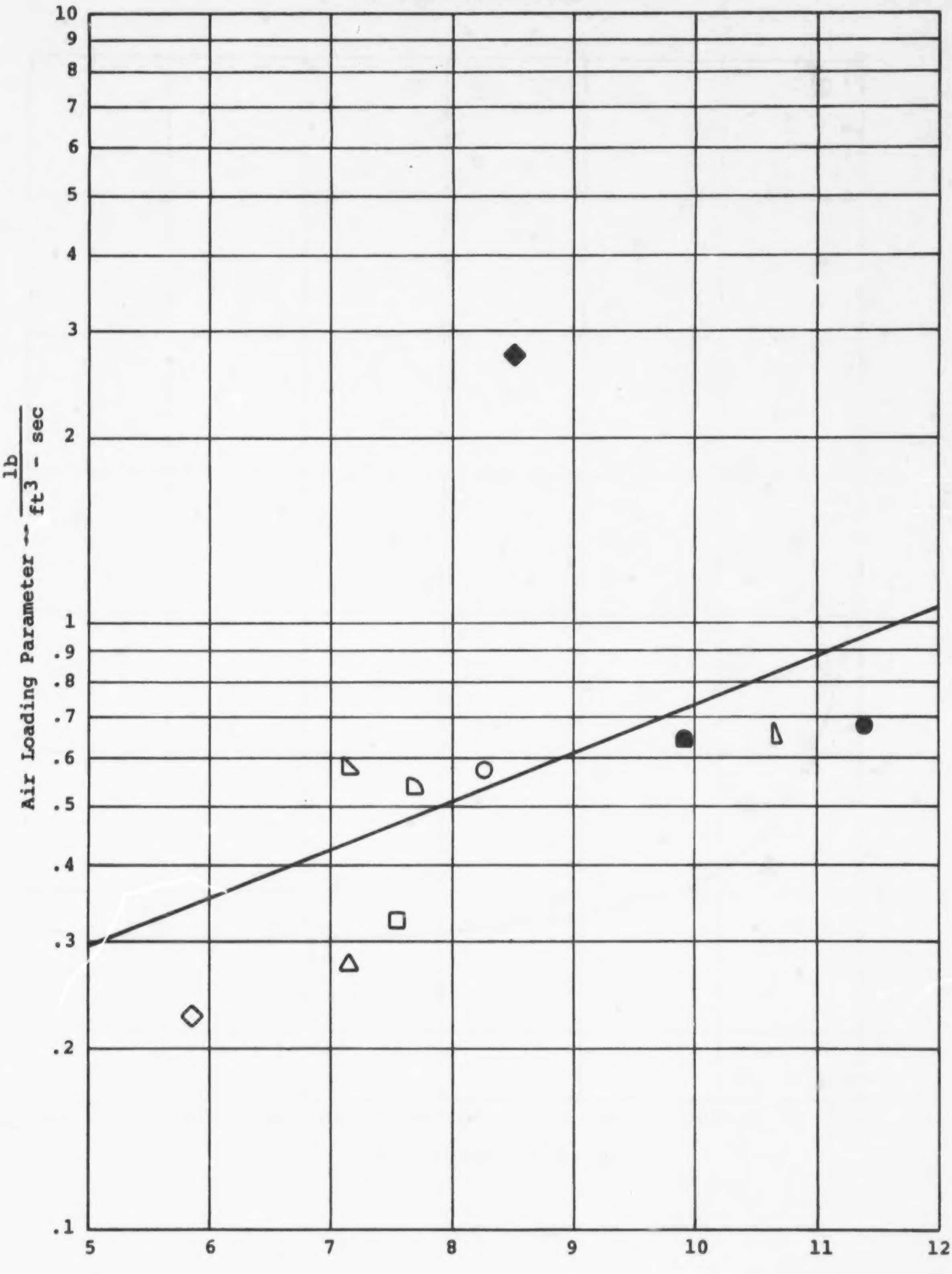
AIR LOADING PARAMETER AS A FUNCTION OF IDLE PRESSURE RATIO PRODUCTION ENGINES



Idle Pressure Ratio

Figure 22

AIR LOADING PARAMETER AS A FUNCTION OF SURFACE TO VOLUME RATIO PRODUCTION ENGINES



Surface to Volume Ratio ~ ft^{-1}

Figure 23

RATED TSFC AS A FUNCTION OF RATED THRUST PRODUCTION ENGINES

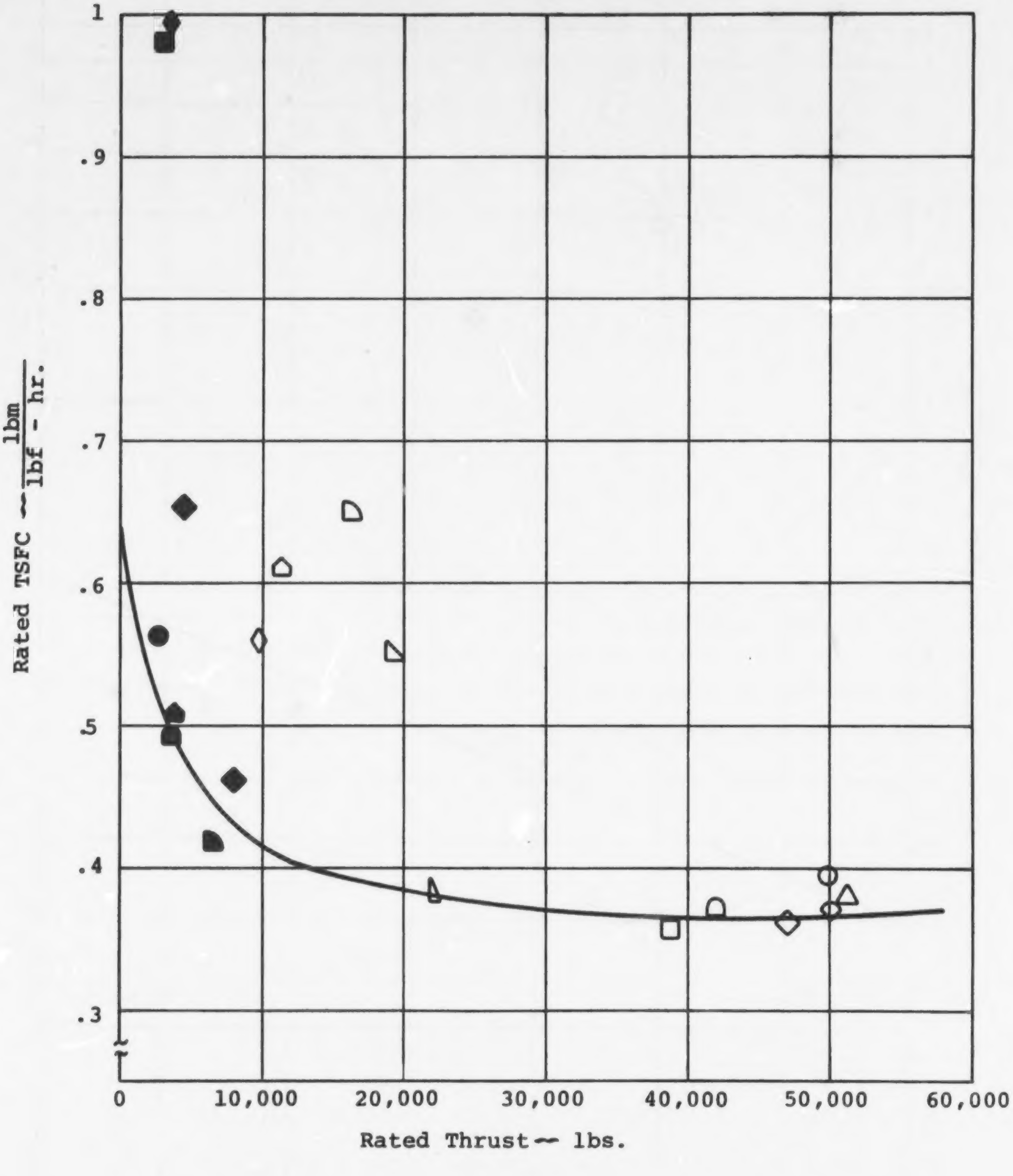


Figure 24

NOx EMISSIONS INDEX AS A FUNCTION OF RATED THRUST
PRODUCTIONS ENGINES

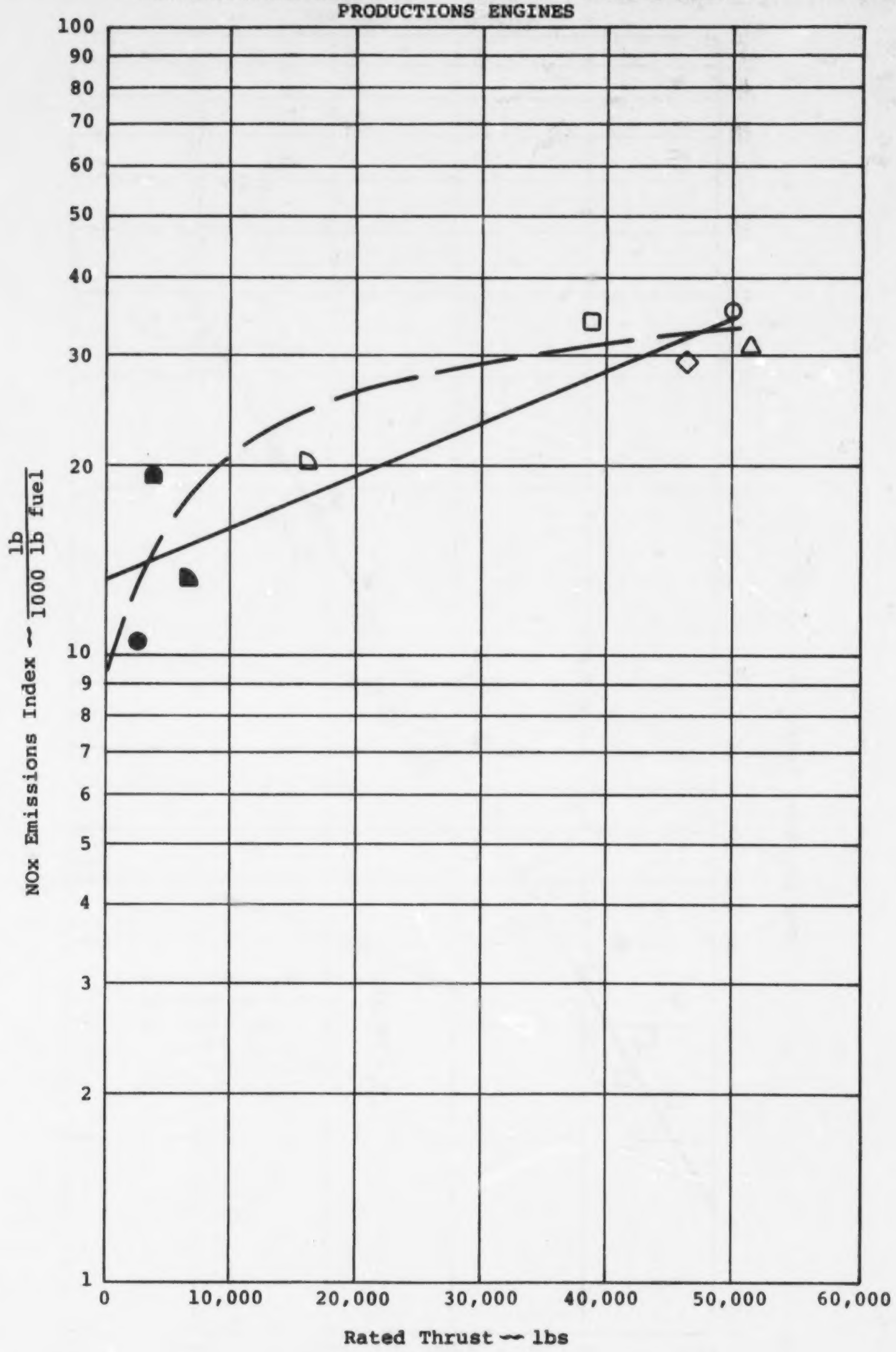
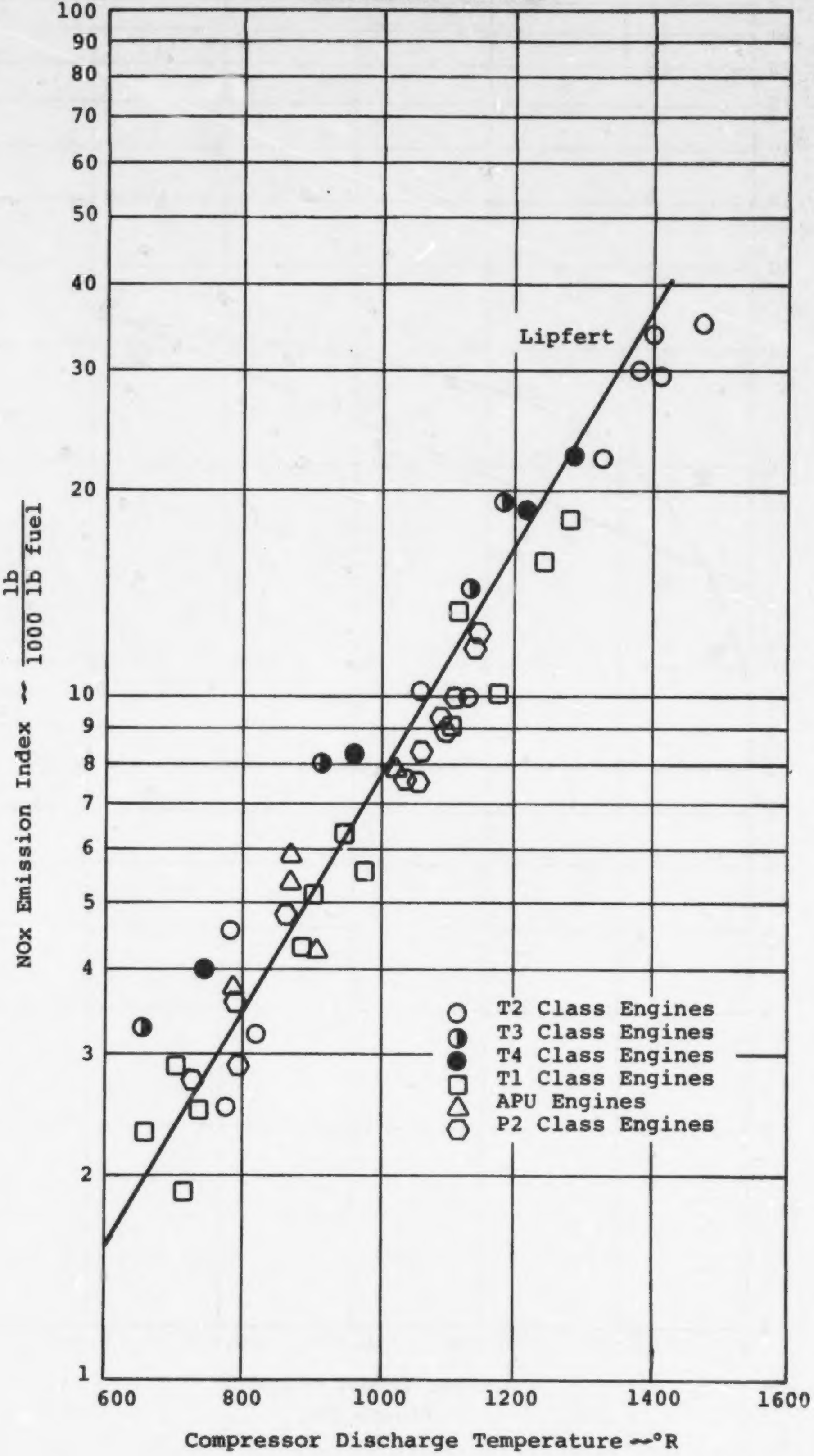


Figure 25



NOx EMISSIONS INDEX AS A FUNCTION OF COMPRESSOR DISCHARGE TEMPERATURE
PRODUCTION ENGINES

Figure 26

NOx EMISSIONS INDEX AS A FUNCTION OF PRESSURE RATIO PRODUCTION ENGINES

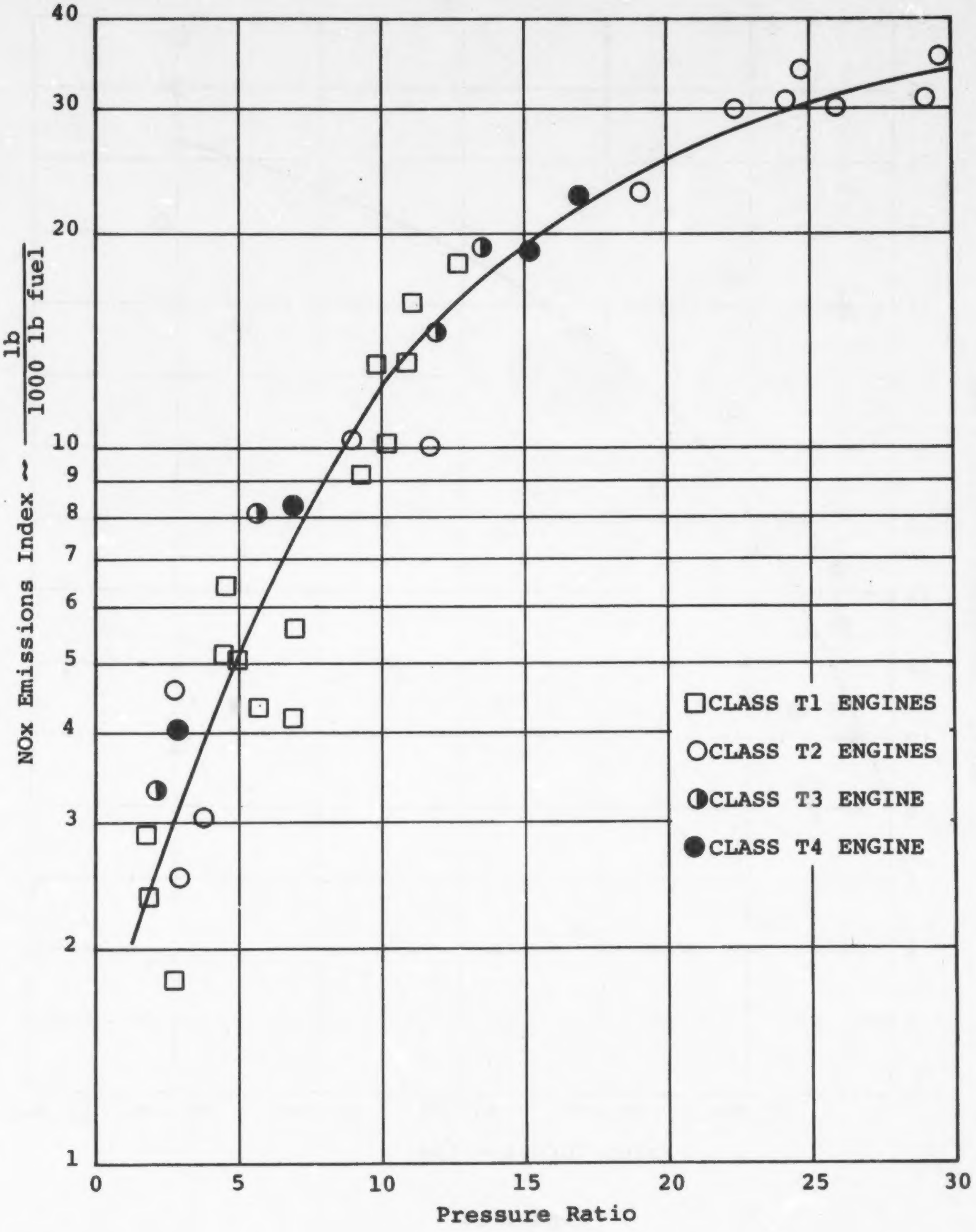


Figure 27

RATED COMPRESSOR PRESSURE RATIO AS A FUNCTION OF RATED THRUST

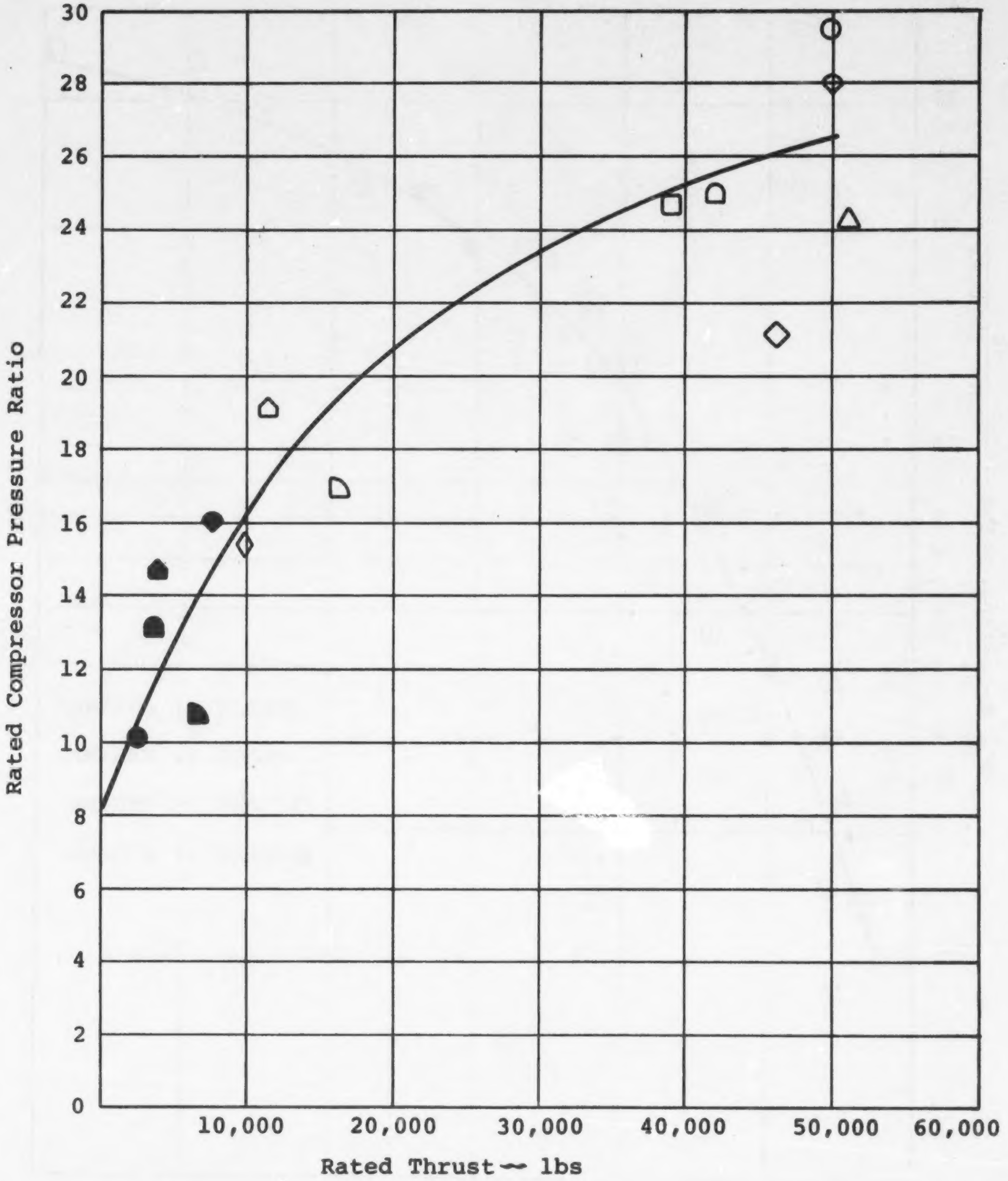


Figure 28

HC EPAP AS A FUNCTION OF RATED THRUST

TECHNOLOGY CATEGORY 1

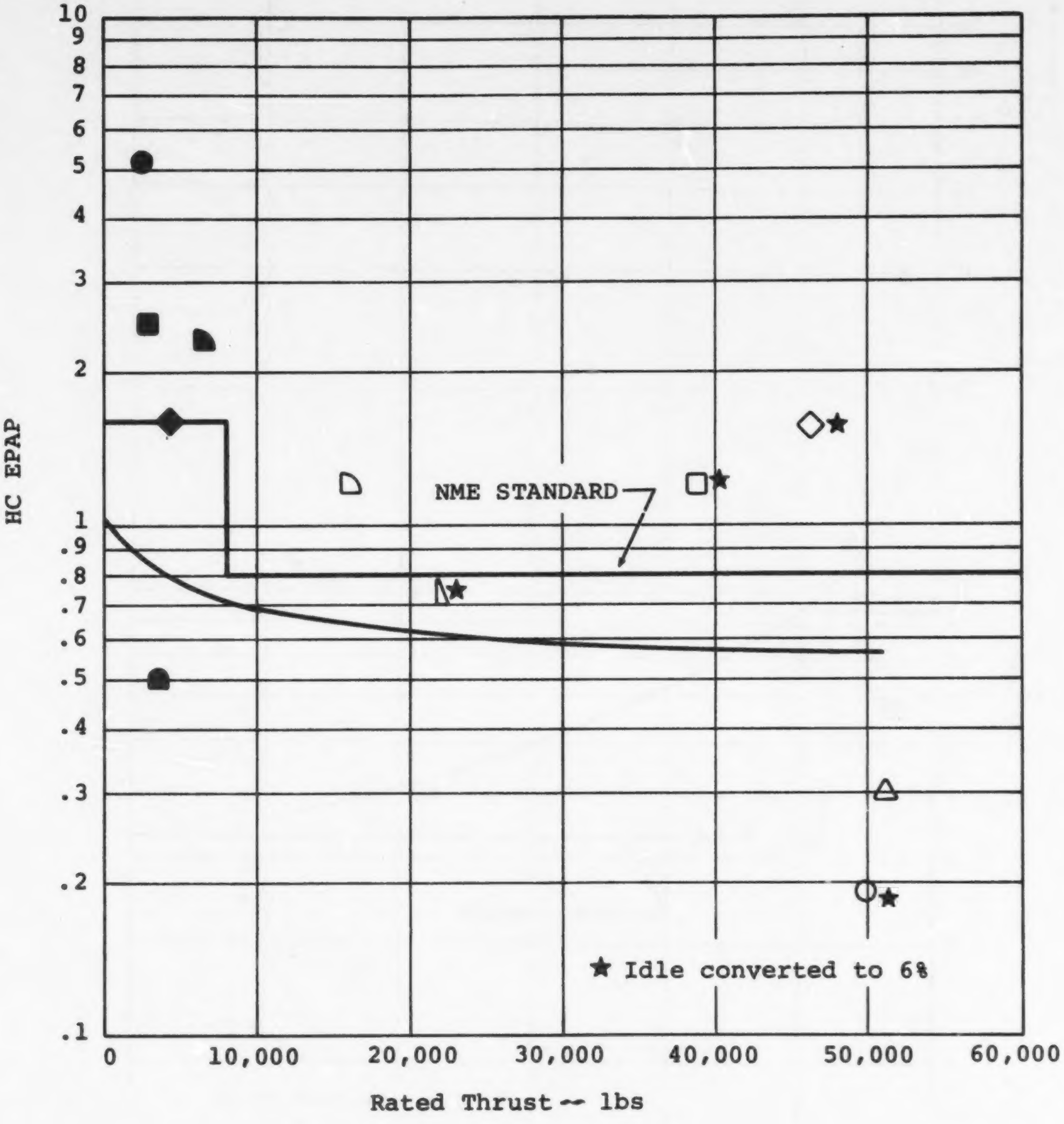
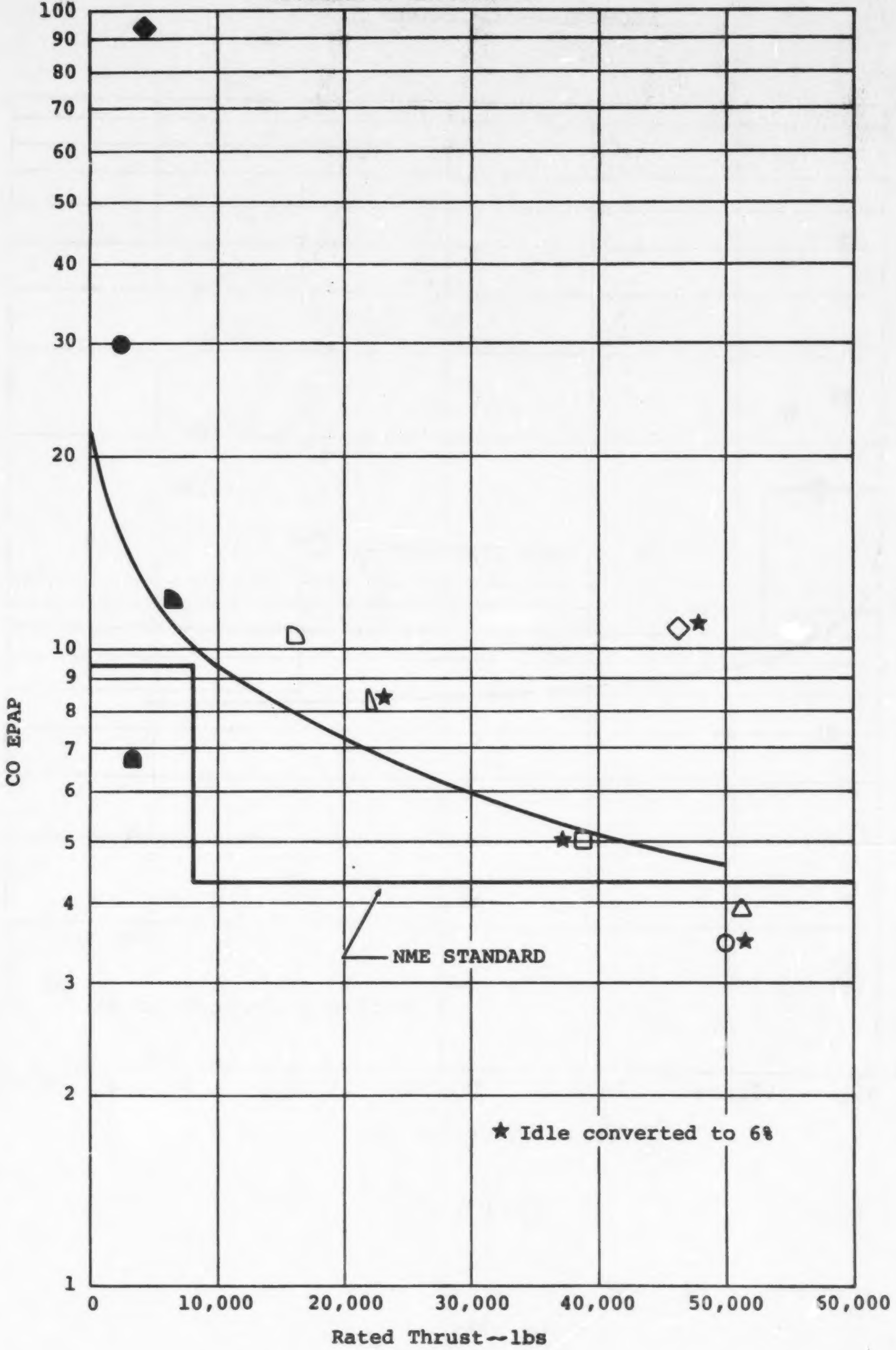


Figure 29

CO EPAP AS A FUNCTION OF RATED THRUST

TECHNOLOGY CATEGORY 1



Rated Thrust—lbs
Figure 30

HC EPAP AS A FUNCTION OF RATED THRUST

TECHNOLOGY CATEGORY 2

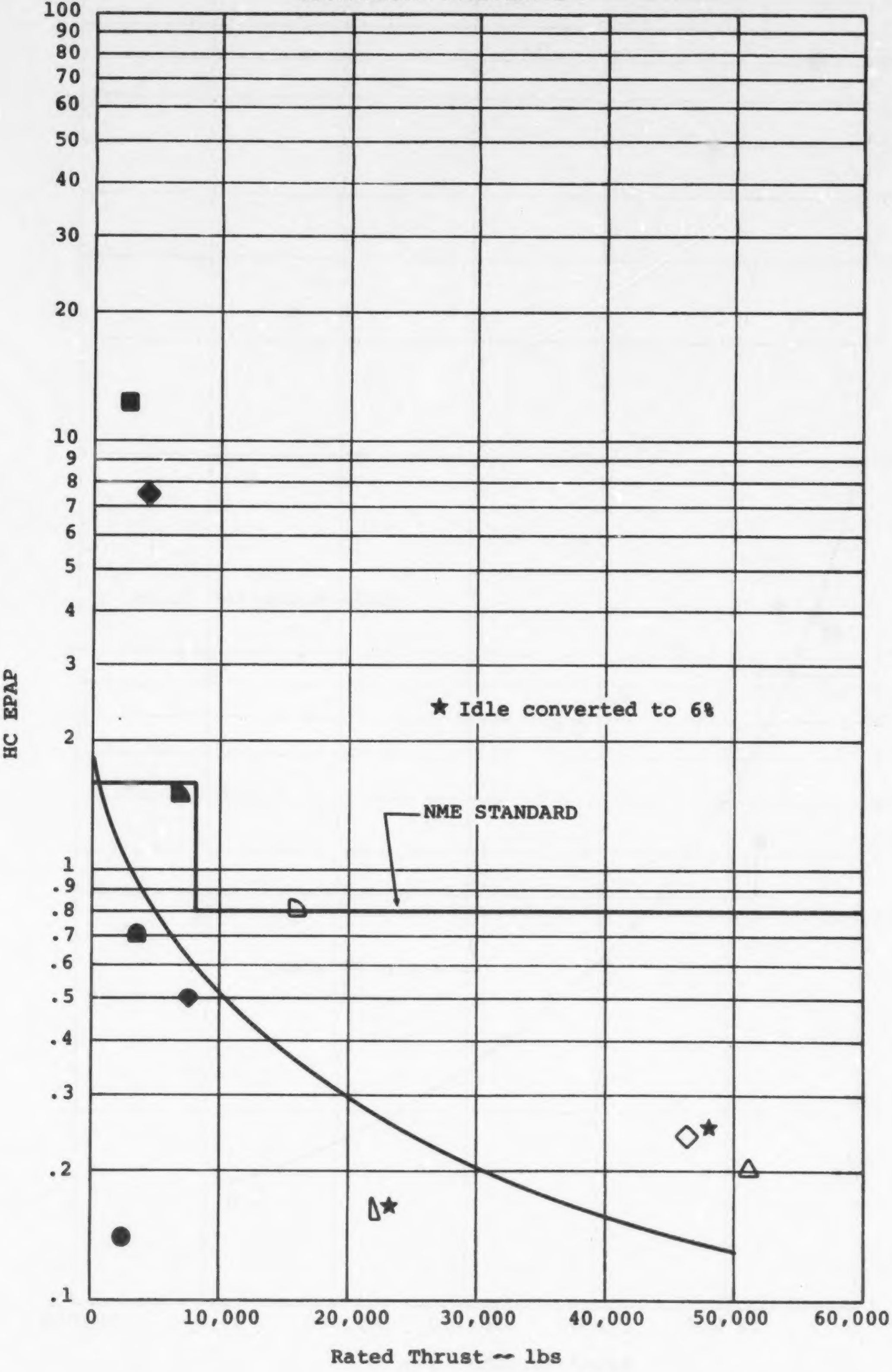
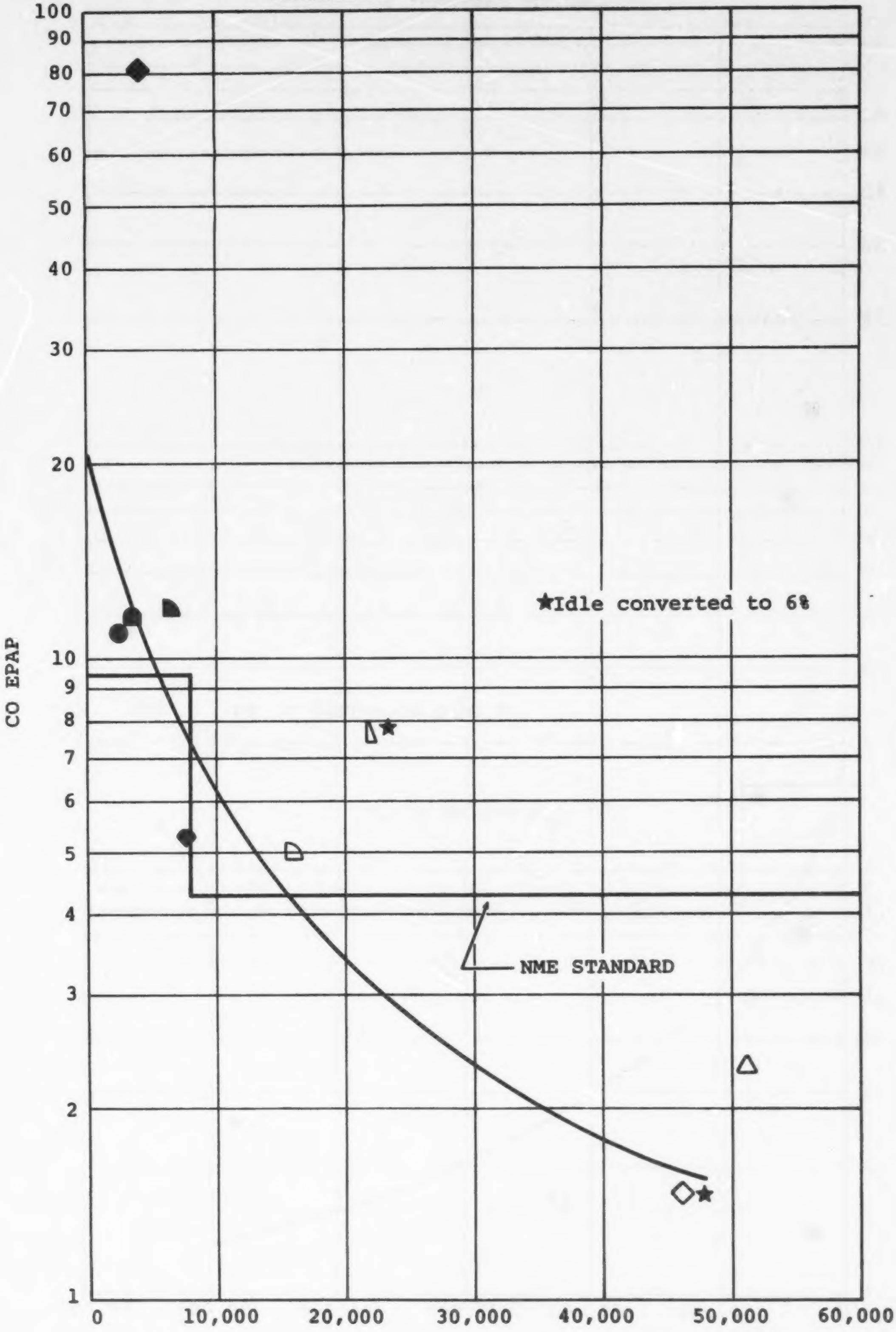


Figure 31

CO EPAP AS A FUNCTION OF RATED THRUST

TECHNOLOGY CATEGORY 2



Rated Thrust — lbs
Figure 32

NOx EPAP AS A FUNCTION OF RATED THRUST

TECHNOLOGY CATEGORY 3

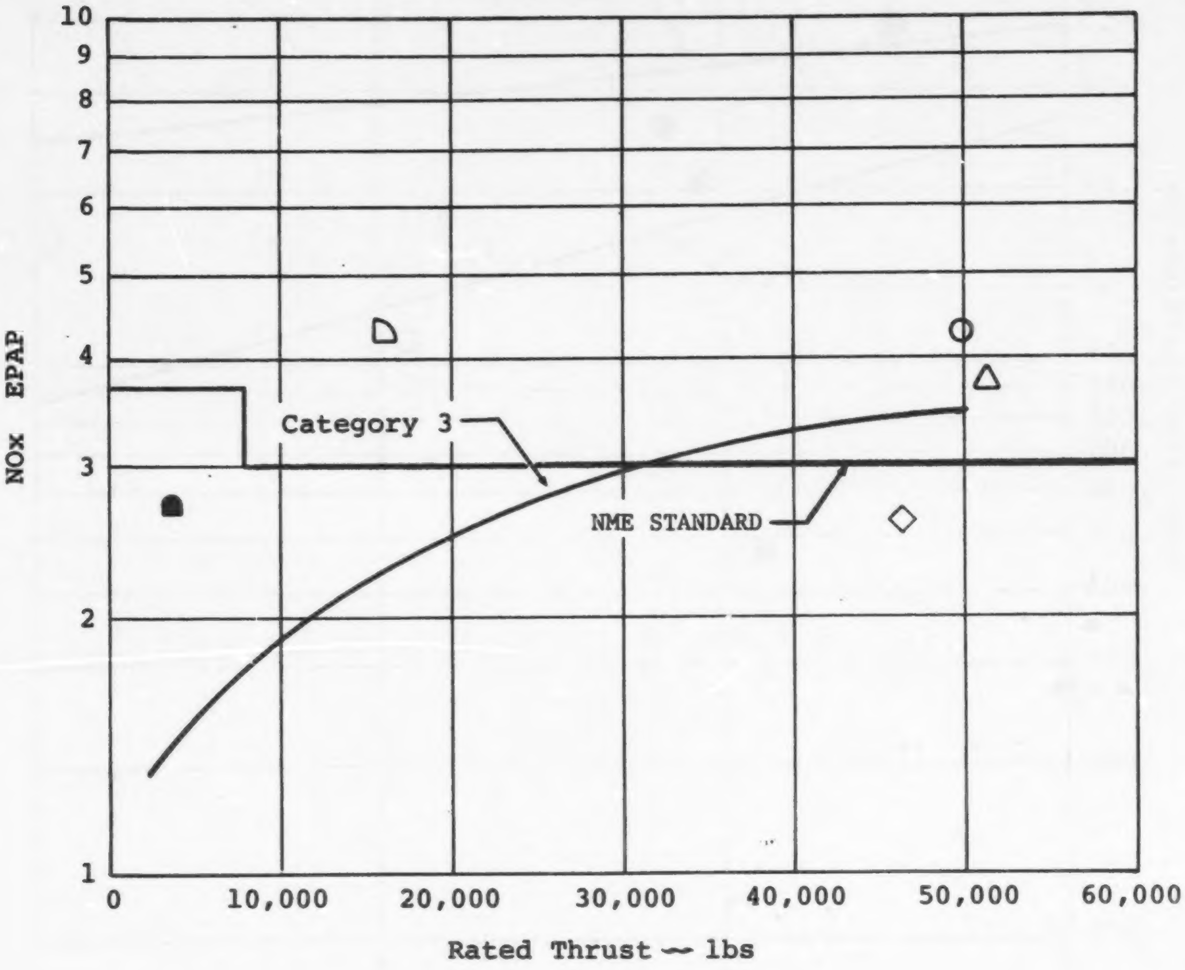


Figure 33

COMBUSTION INEFFICIENCY AS A FUNCTION OF IDLE PRESSURE RATIO

TECHNOLOGY CATEGORY 1

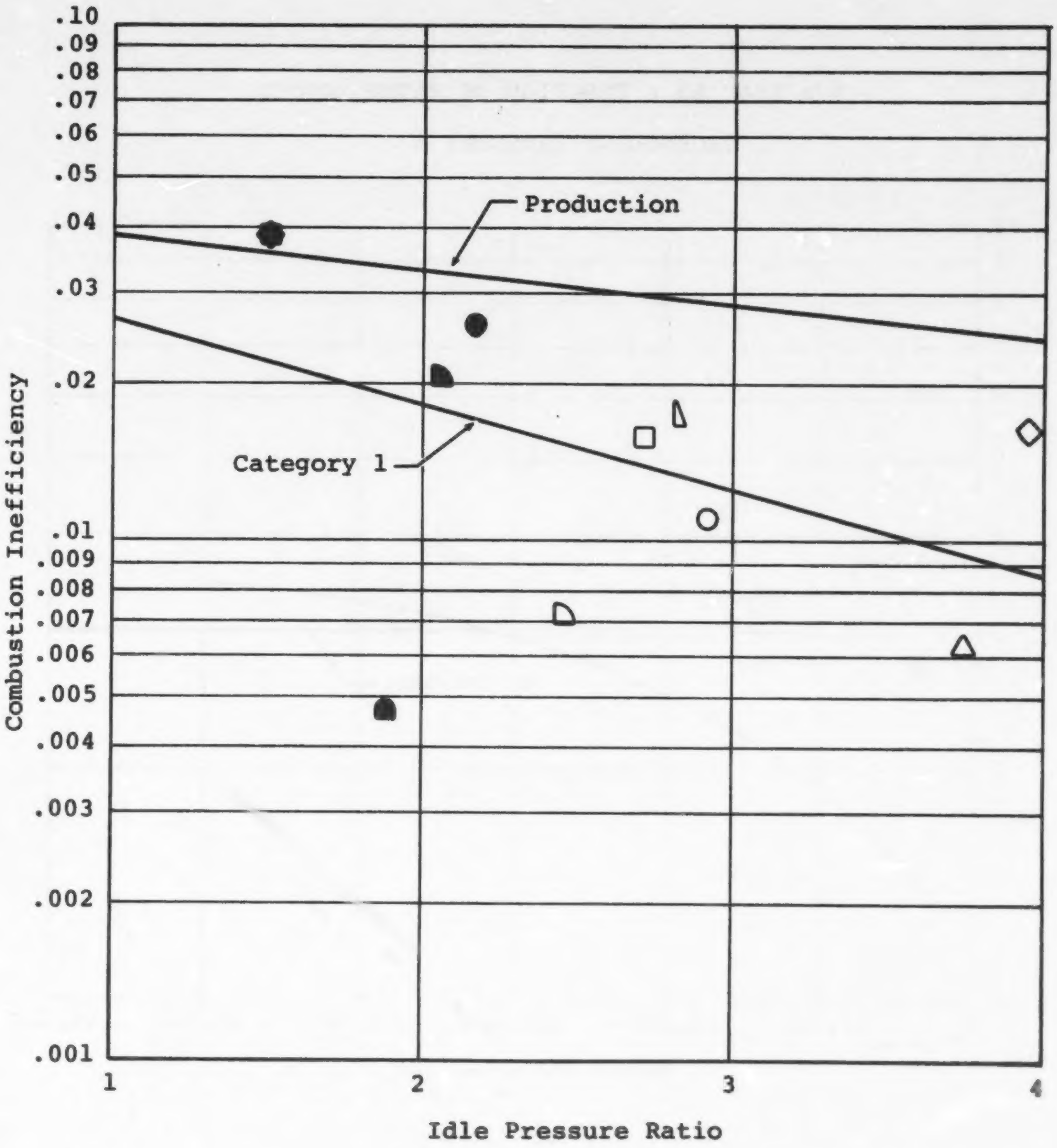


Figure 34

HC EMISSIONS INDEX AT IDLE AS FUNCTION OF IDLE PRESSURE RATIO

TECHNOLOGY CATEGORY 1

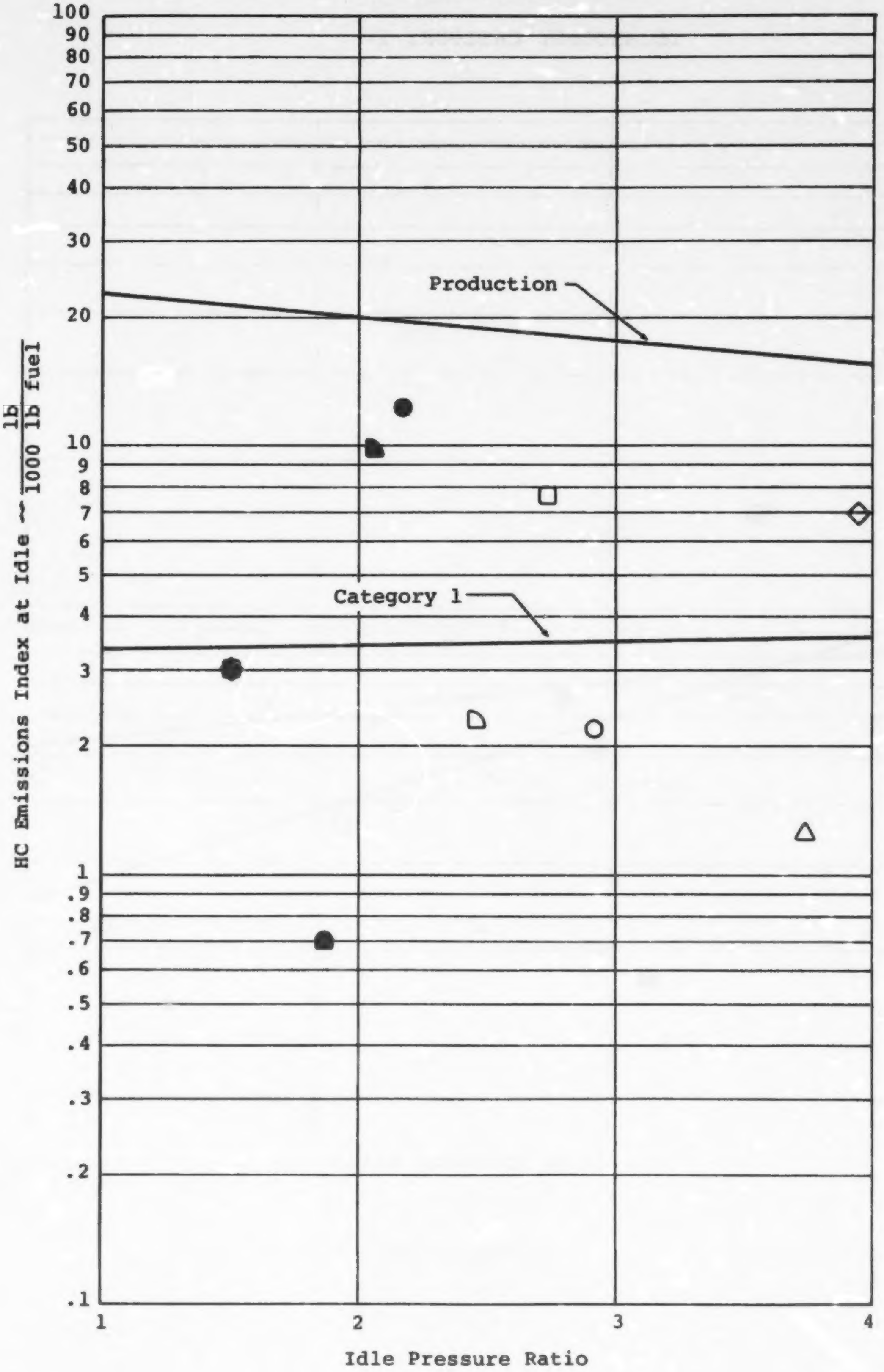


Figure 35

CO EMISSIONS INDEX AT IDLE AS A FUNCTION OF IDLE PRESSURE RATIO

TECHNOLOGY CATEGORY 1

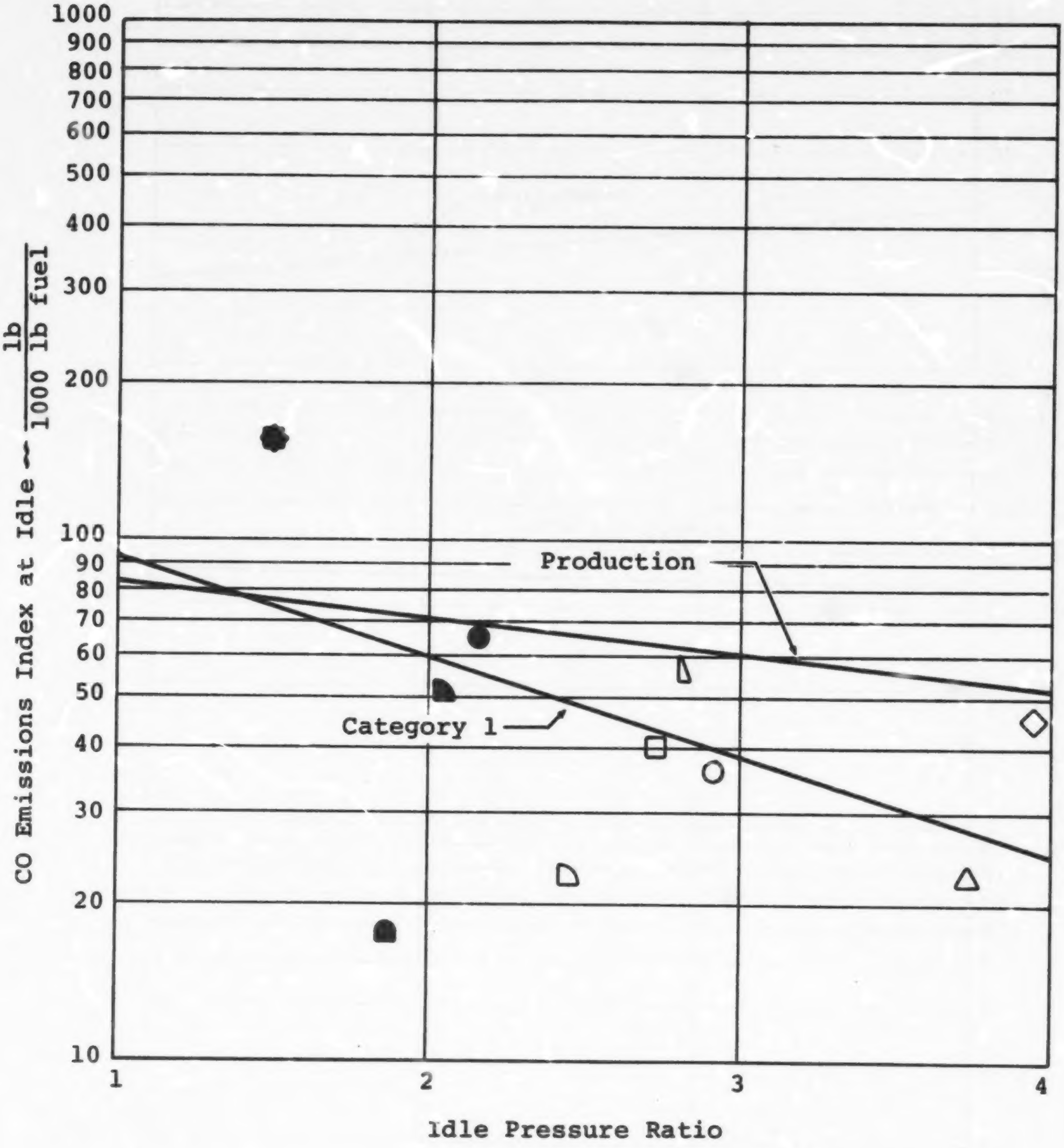


Figure 36

COMBUSTION INEFFICIENCY AS A FUNCTION OF IDLE PRESSURE RATIO

TECHNOLOGY CATEGORY 2

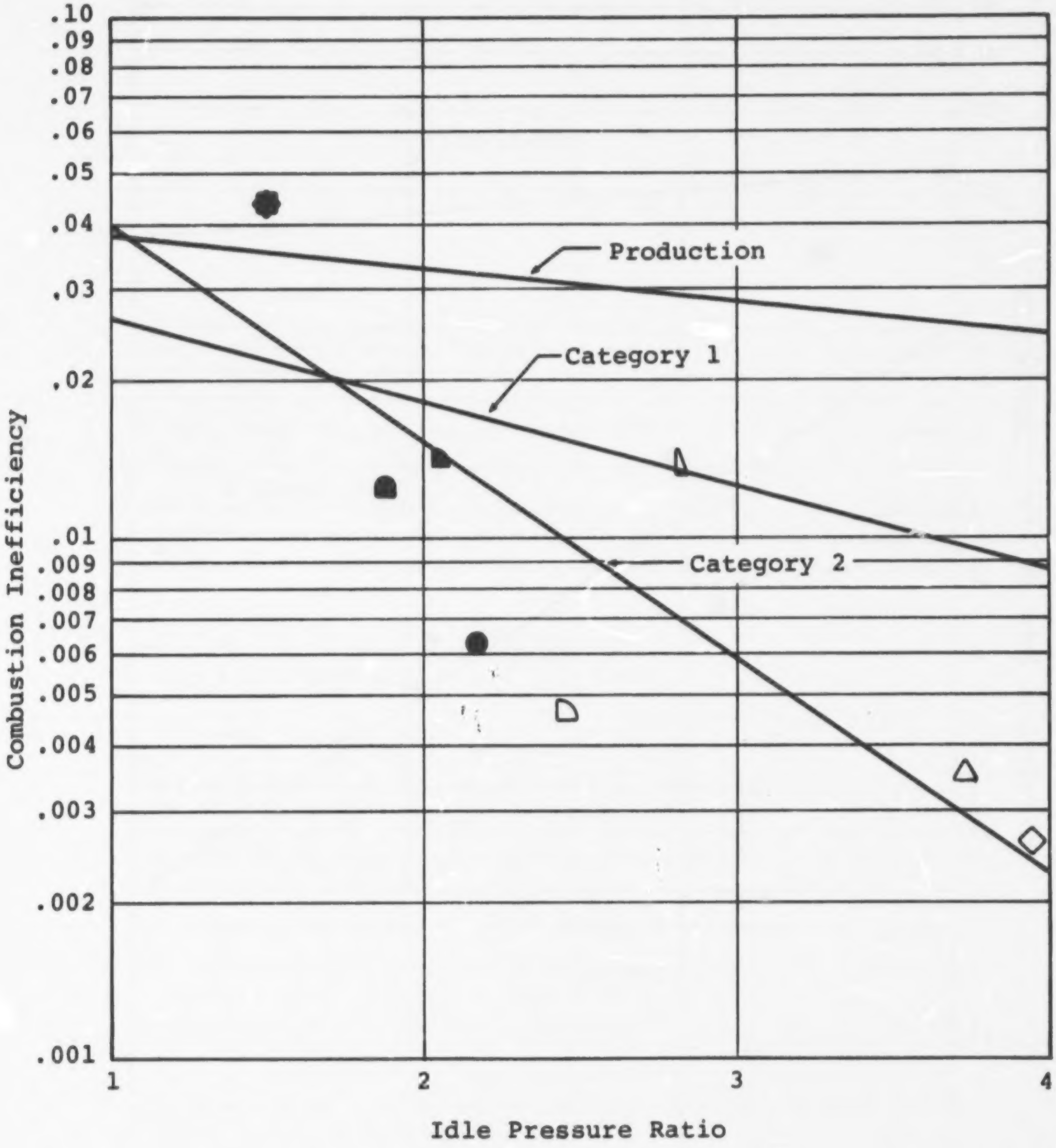


Figure 37

HC EMISSIONS INDEX AT IDLE AS A FUNCTION OF IDLE PRESSURE RATIO

TECHNOLOGY CATEGORY 2

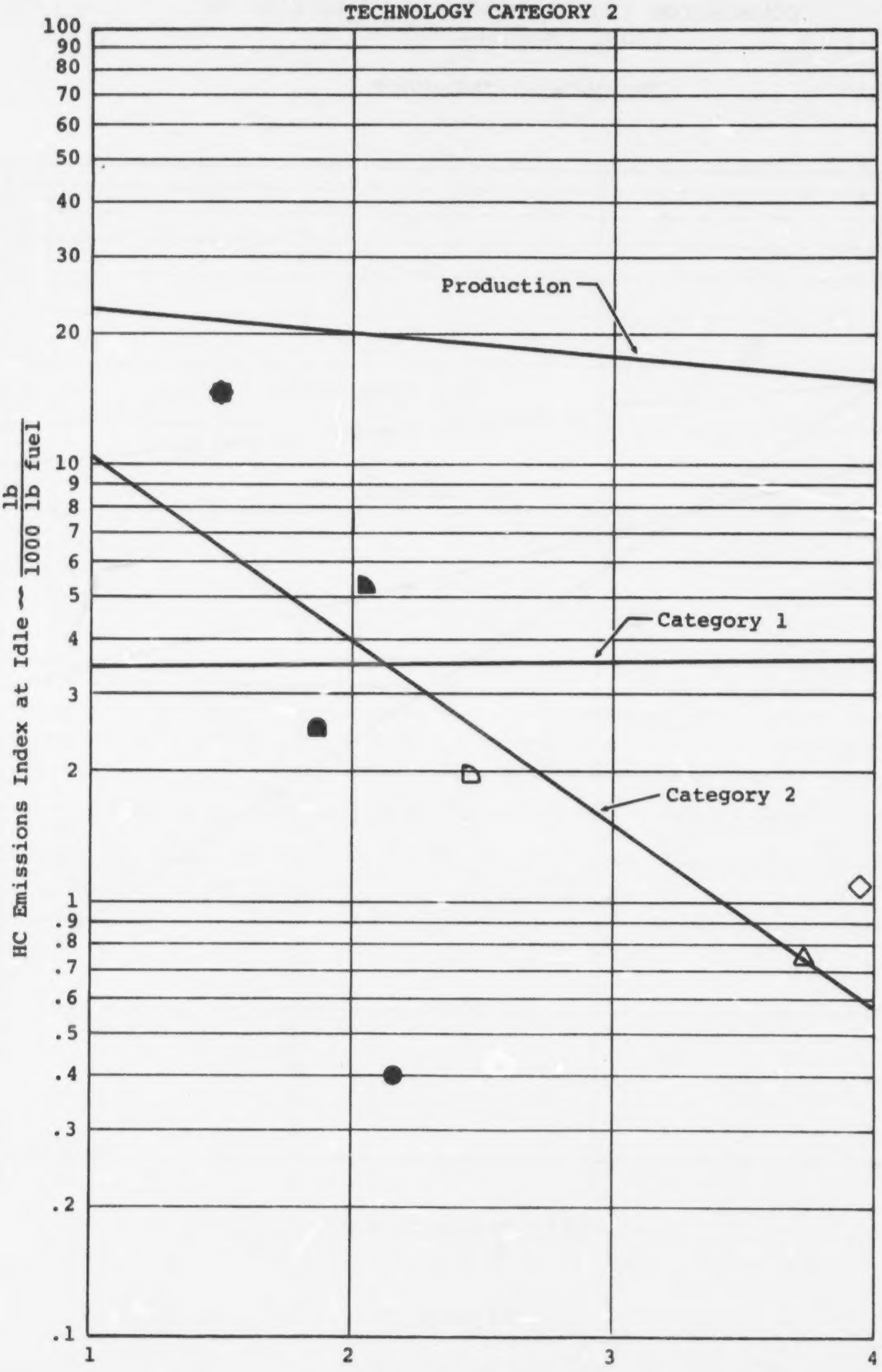


Figure 38

CO EMISSIONS INDEX AT IDLE AS A FUNCTION OF IDLE PRESSURE RATIO

TECHNOLOGY CATEGORY 2

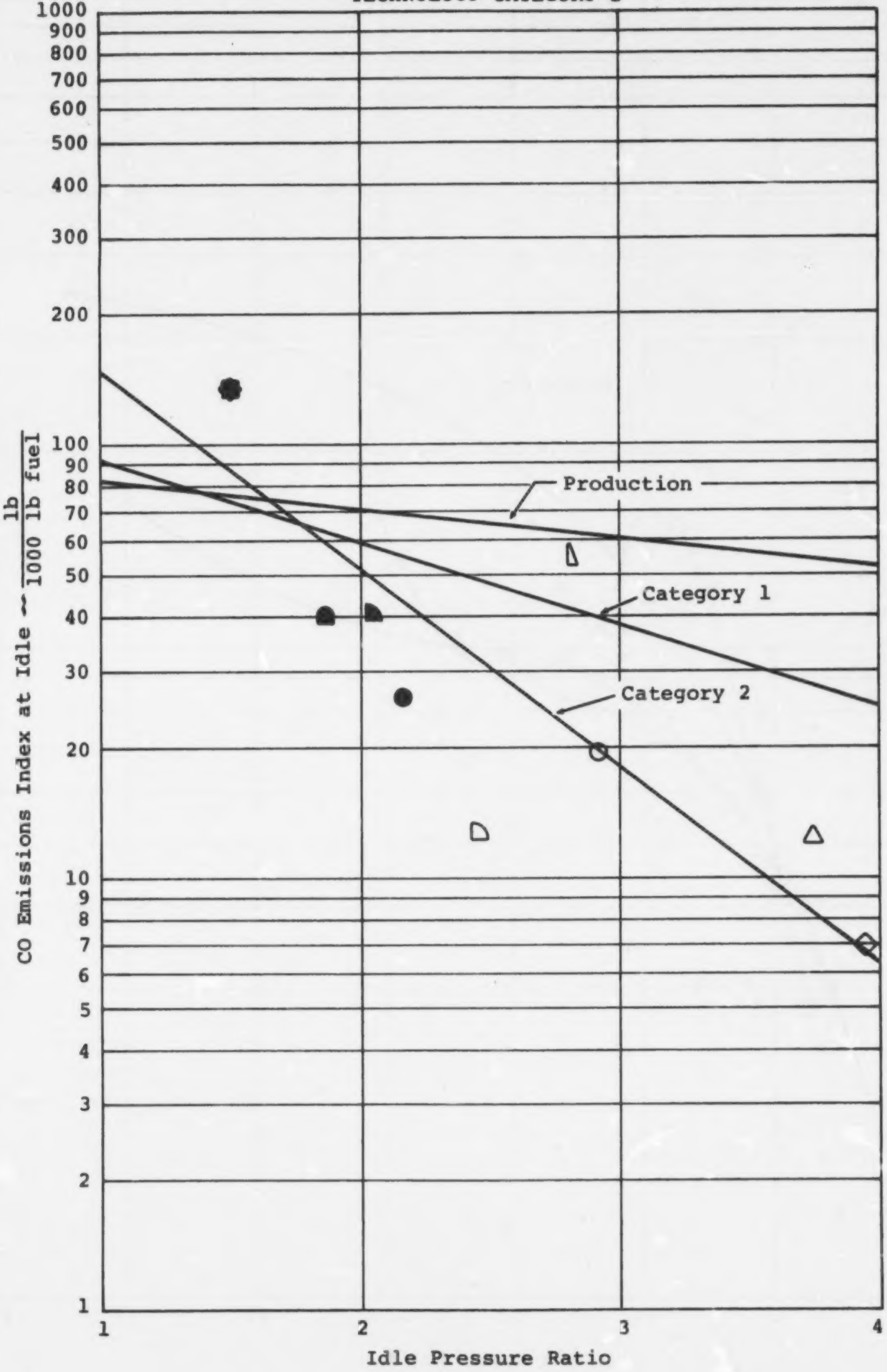


Figure 39

NOx EMISSIONS INDEX AS A FUNCTION OF PRESSURE RATIO

TECHNOLOGY CATEGORY 3

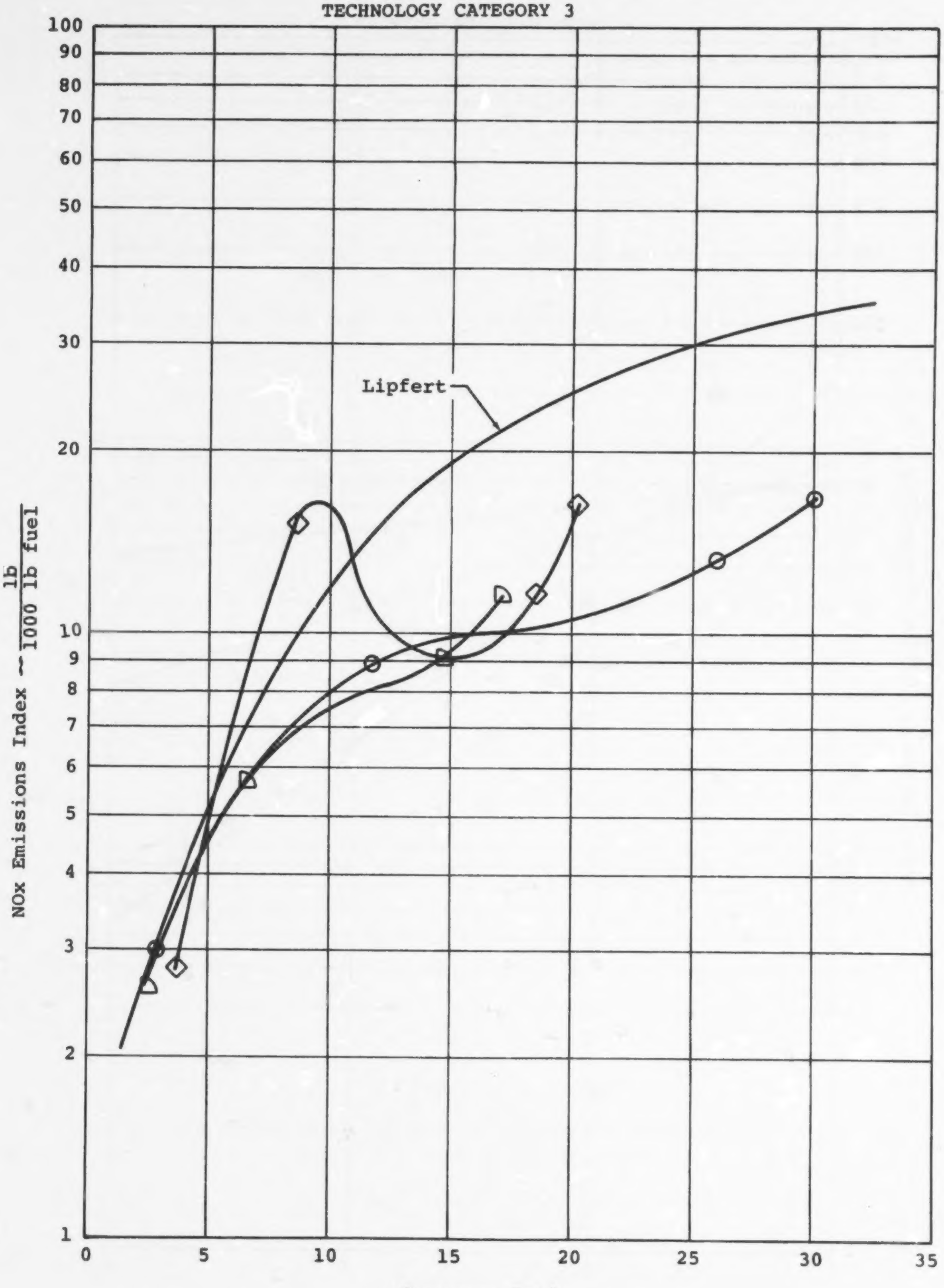


Figure 40

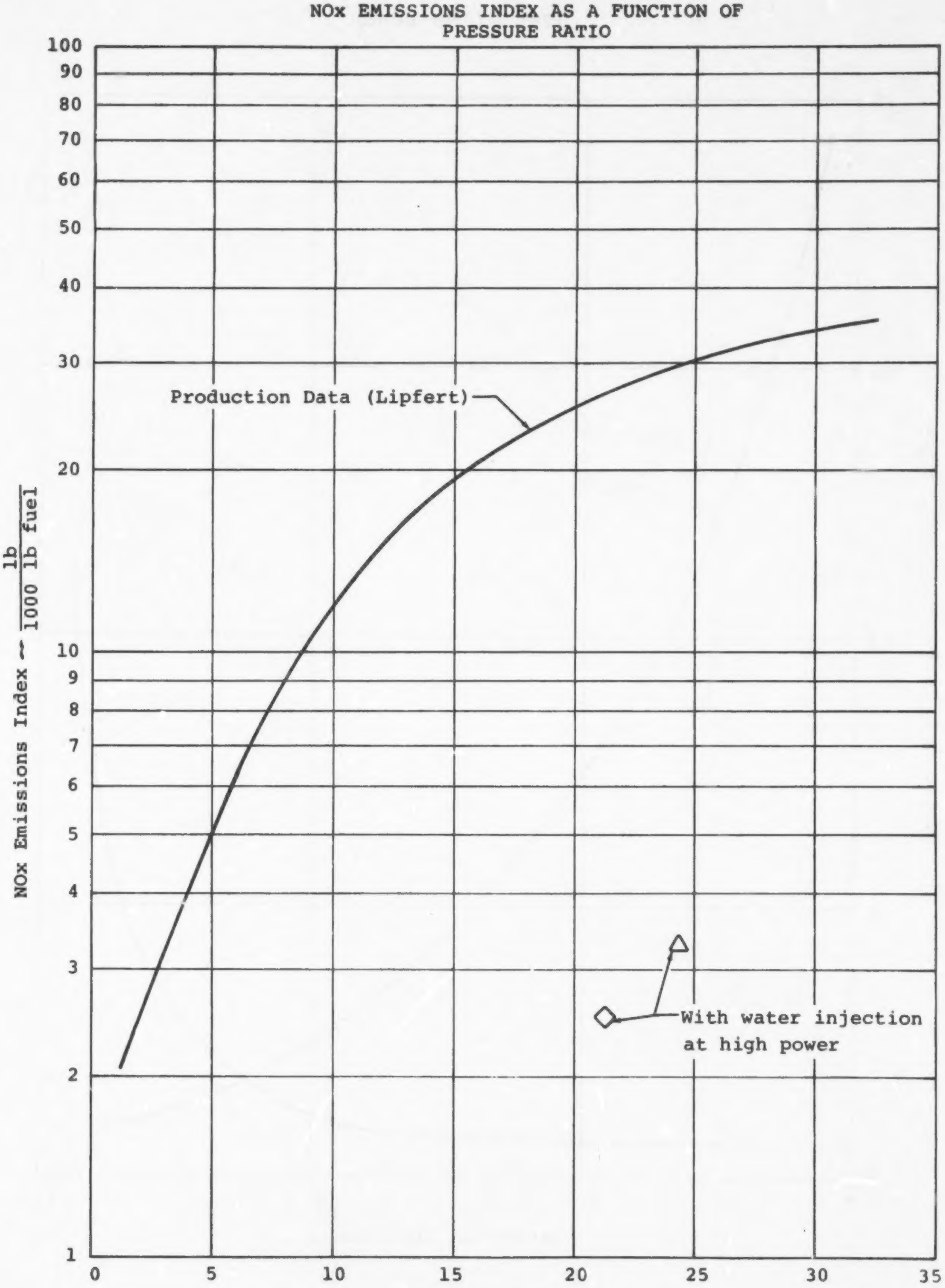

NOx EMISSIONS INDEX AS A FUNCTION OF PRESSURE RATIO
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
NOx Emissions Index ~ lb / 1000 lb fuel
Production Data (Lipfert)
With water injection at high power
0
5
10
15
20
25
30
35
Pressure Ratio

Figure 41

JT9D CLIMB POWER

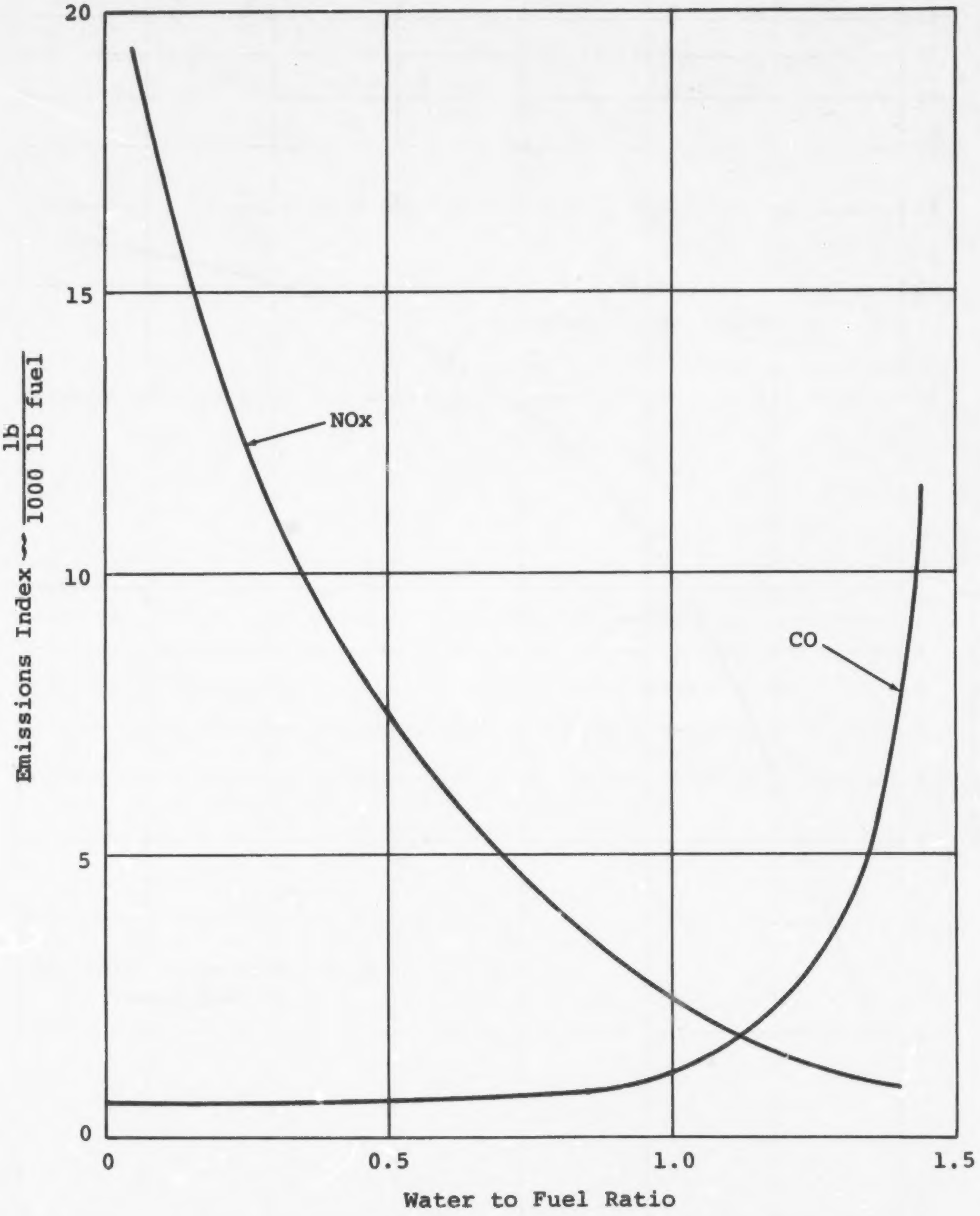
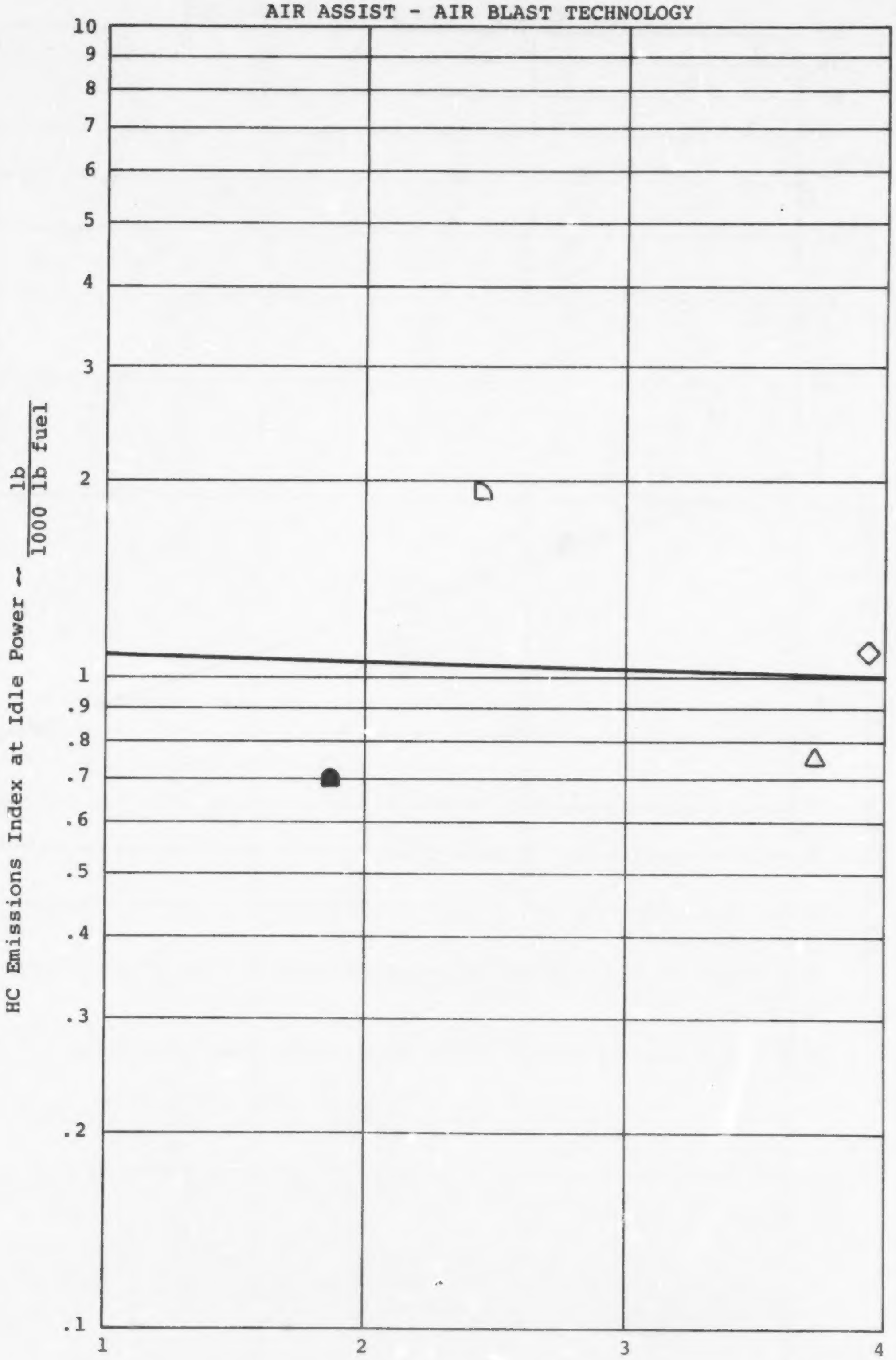


Figure 42

HC EMISSIONS INDEX AT IDLE POWER AS A FUNCTION OF IDLE PRESSURE RATIO

AIR ASSIST - AIR BLAST TECHNOLOGY



Idle Pressure Ratio
Figure 43

CO EMISSIONS INDEX AT IDLE AS A FUNCTION OF IDLE PRESSURE RATIO

AIR ASSIST - AIR BLAST TECHNOLOGY

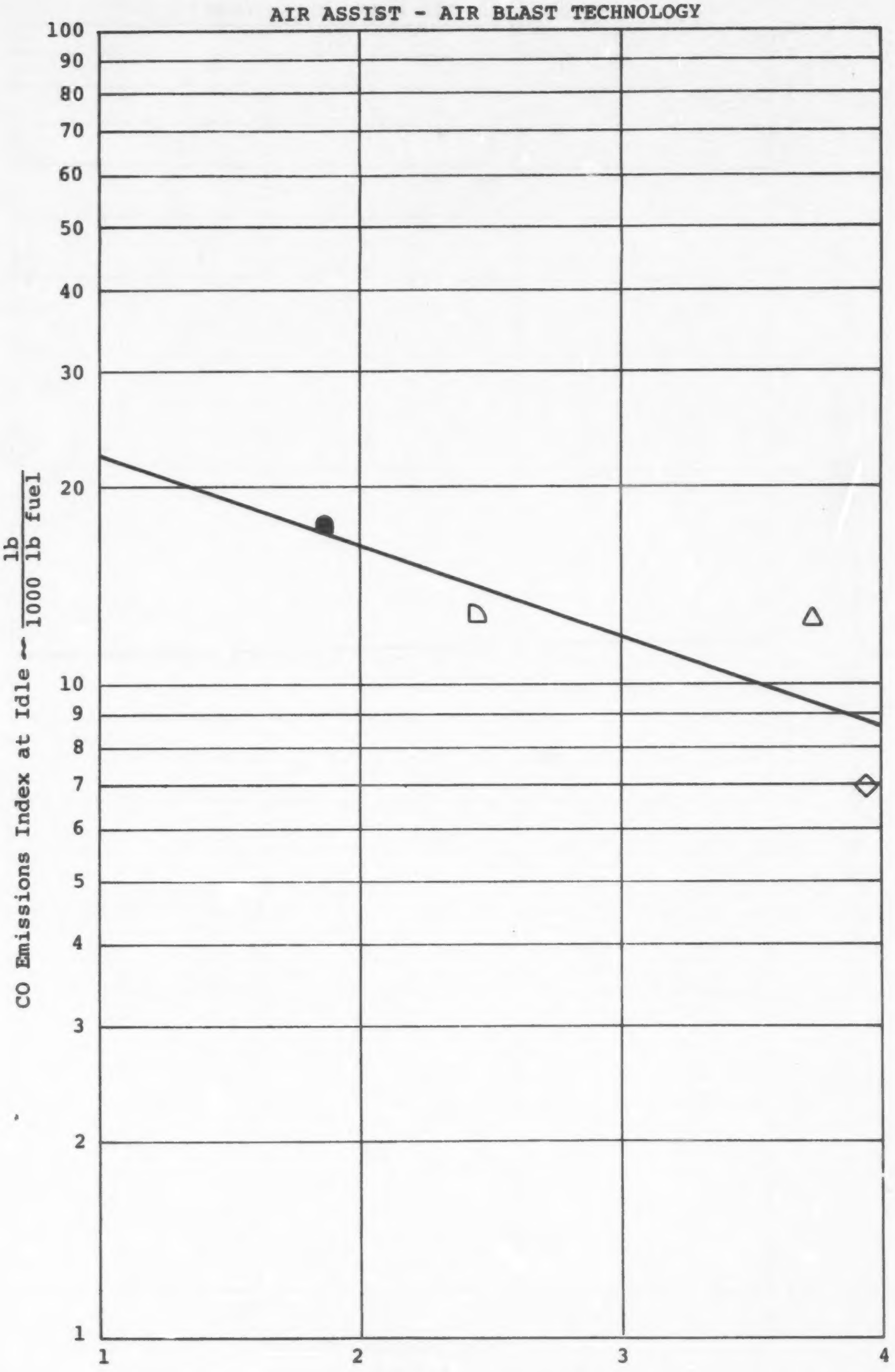


Figure 44

NCE TSFC AS A FUNCTION OF RATED THRUST

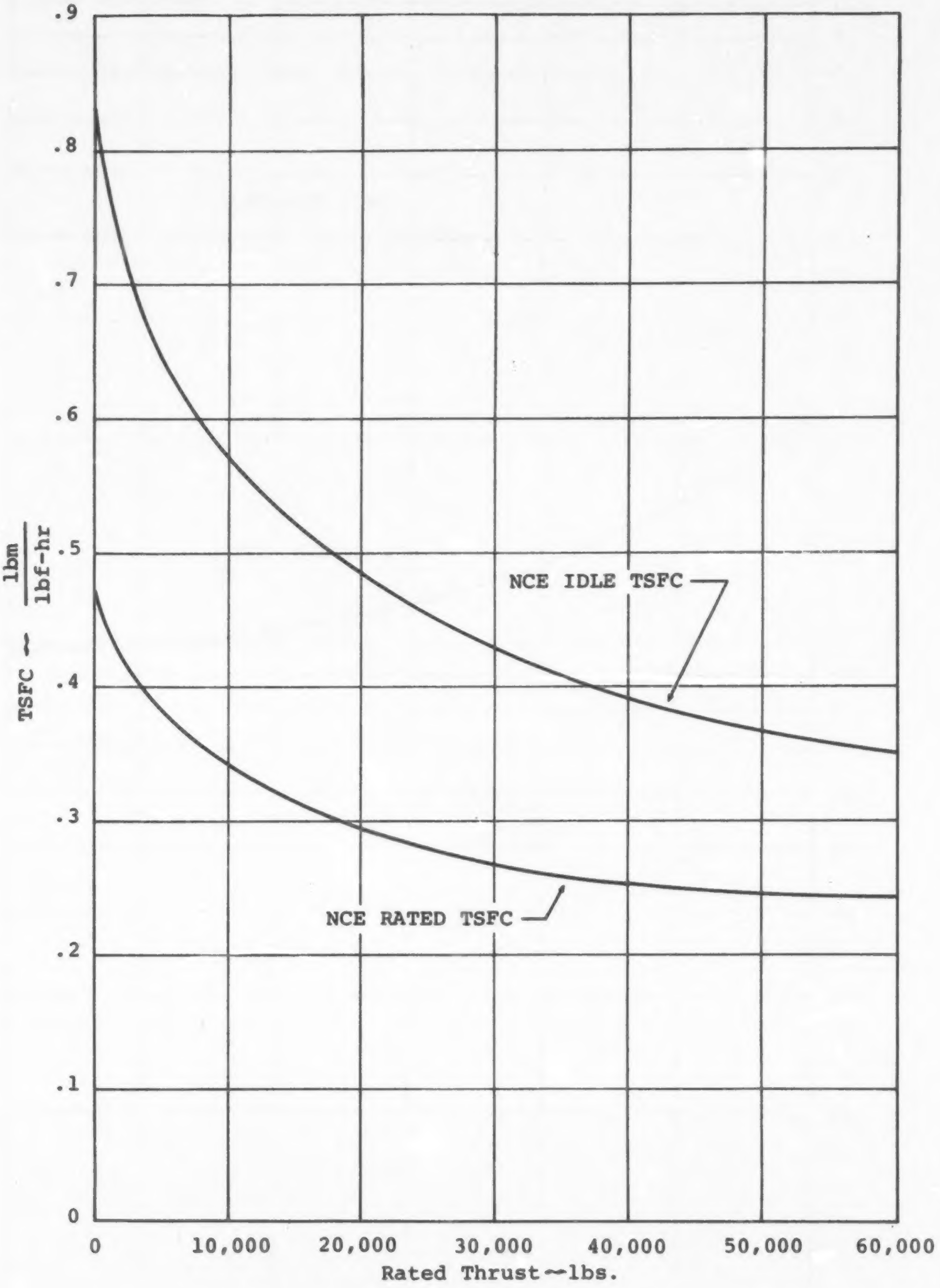


Figure 45

HC EPAP AS A FUNCTION OF RATED THRUST
NEWLY CERTIFIED ENGINES

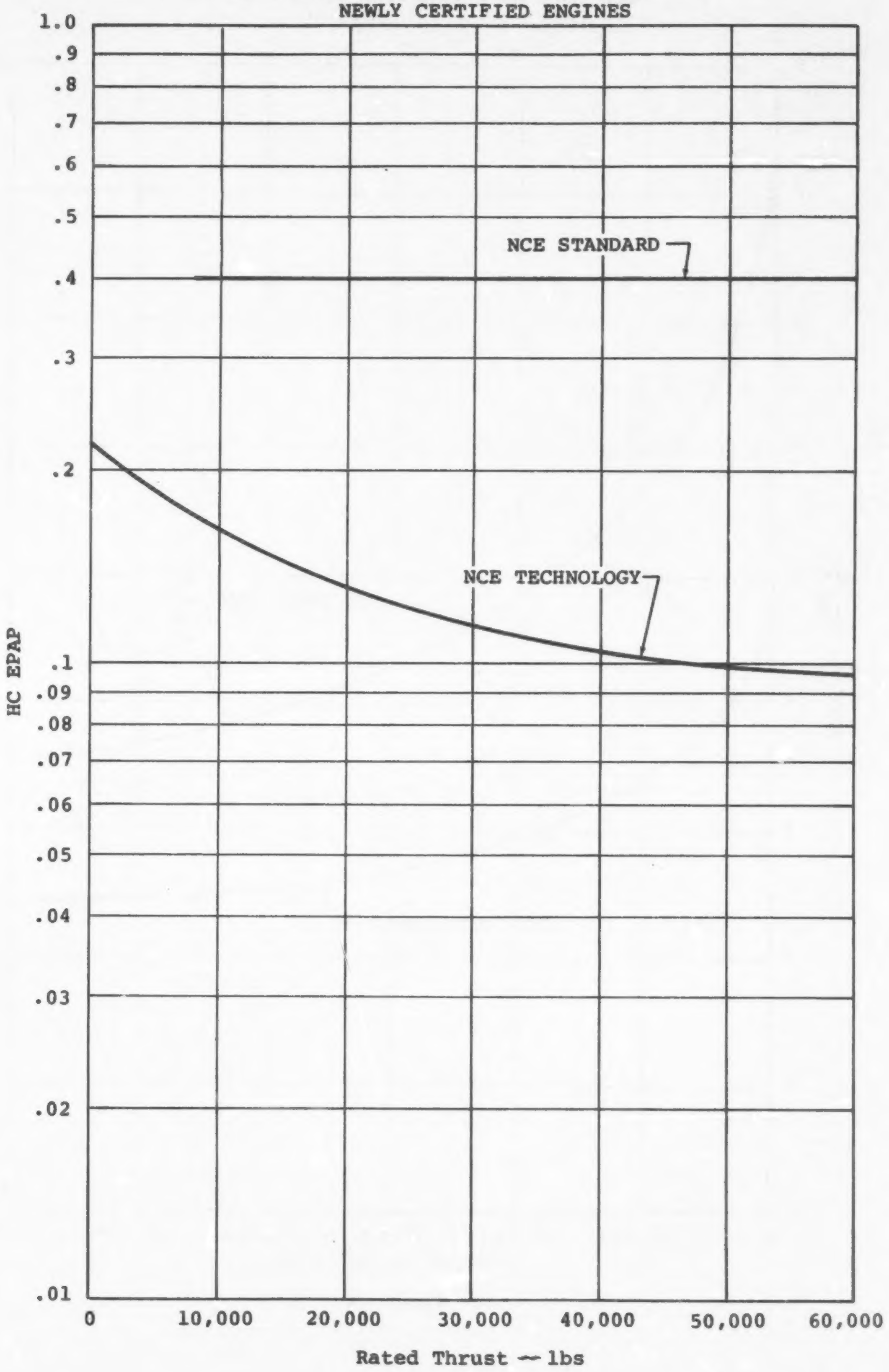


Figure 46

CO EPAP AS A FUNCTION OF RATED THRUST
NEWLY CERTIFIED ENGINES

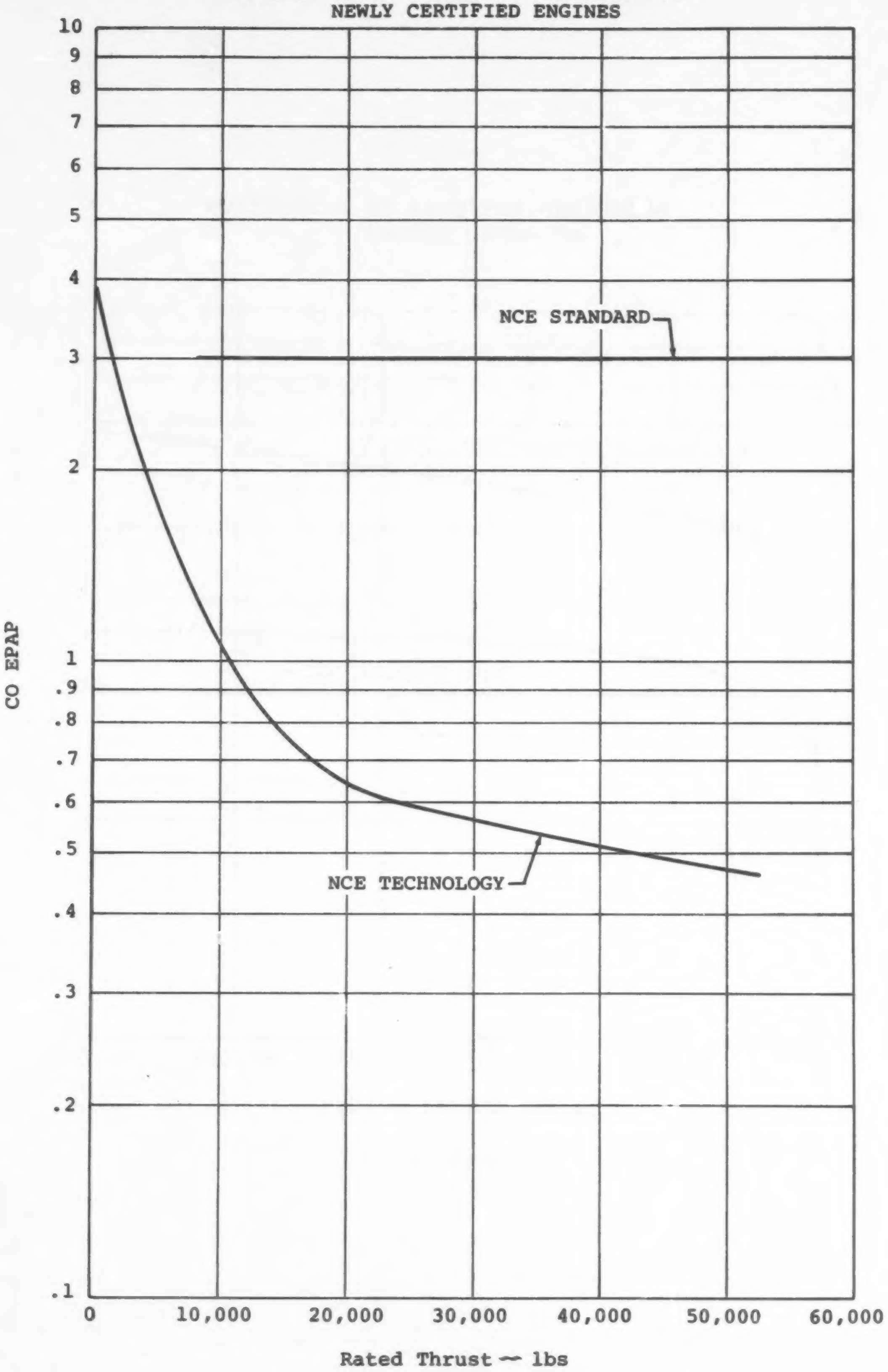


Figure 47

PROJECTED NOx EPAP AS A FUNCTION OF RATED THRUST

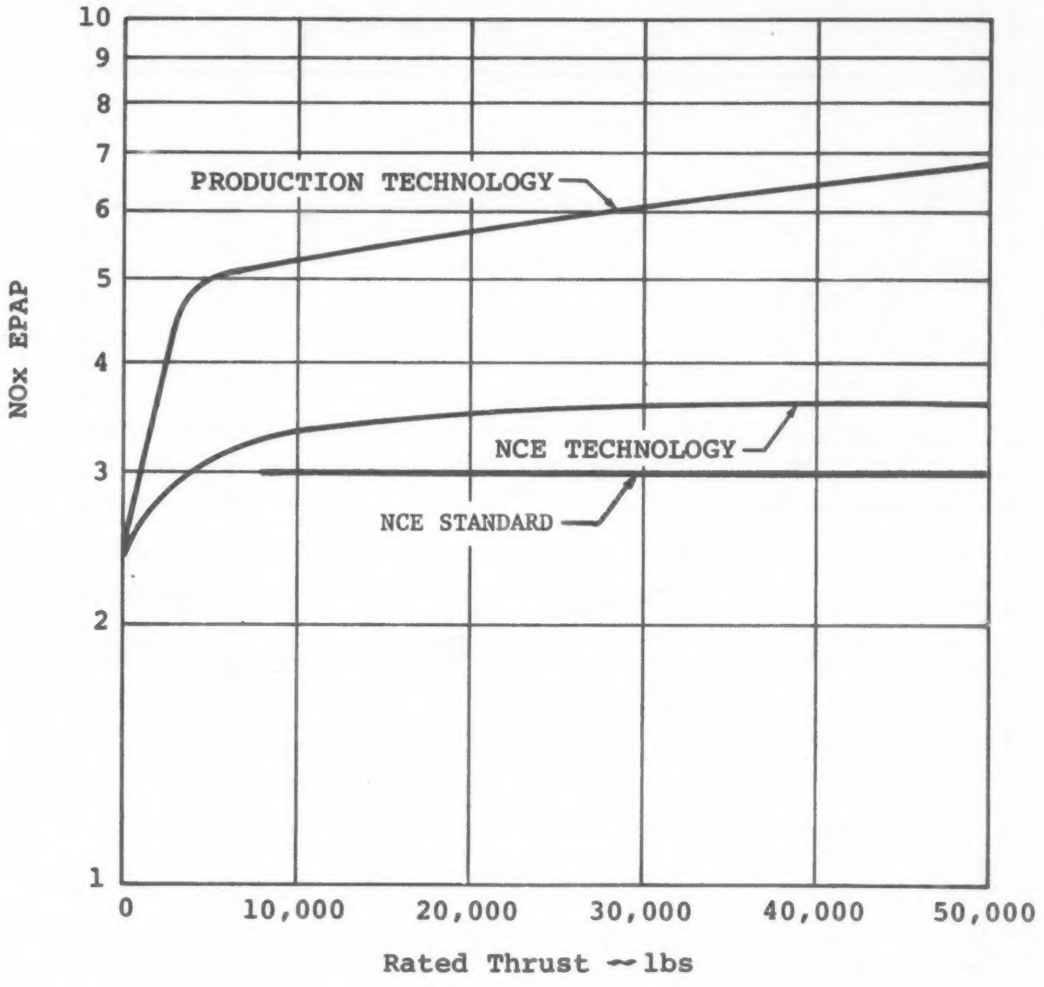


Figure 48

PSFC AS A FUNCTION OF HORSEPOWER
NEWLY CERTIFIED CLASS P2 ENGINES

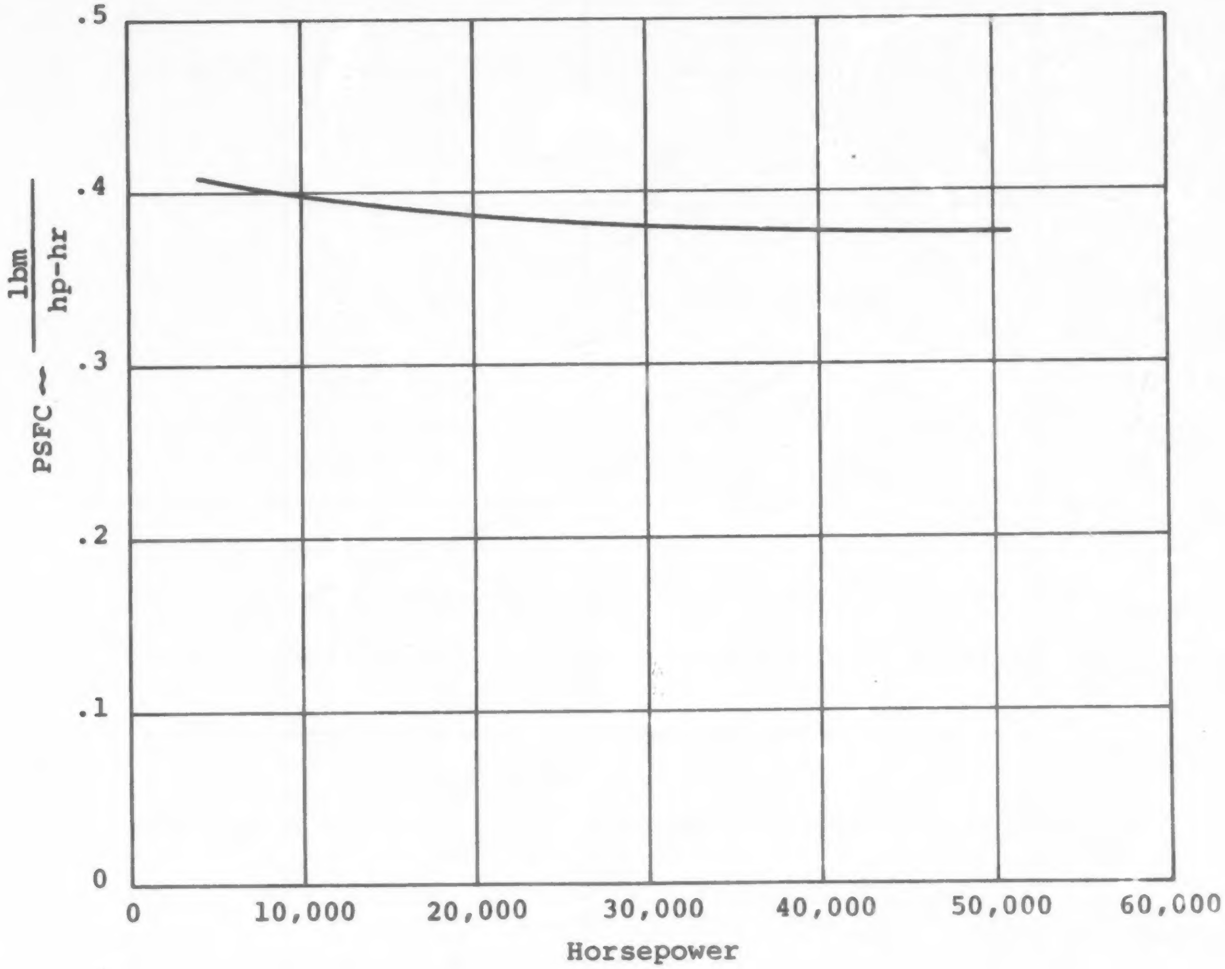


Figure 49

HC EPAP AS A FUNCTION OF HORSEPOWER
NEWLY CERTIFIED CLASS P2 ENGINES

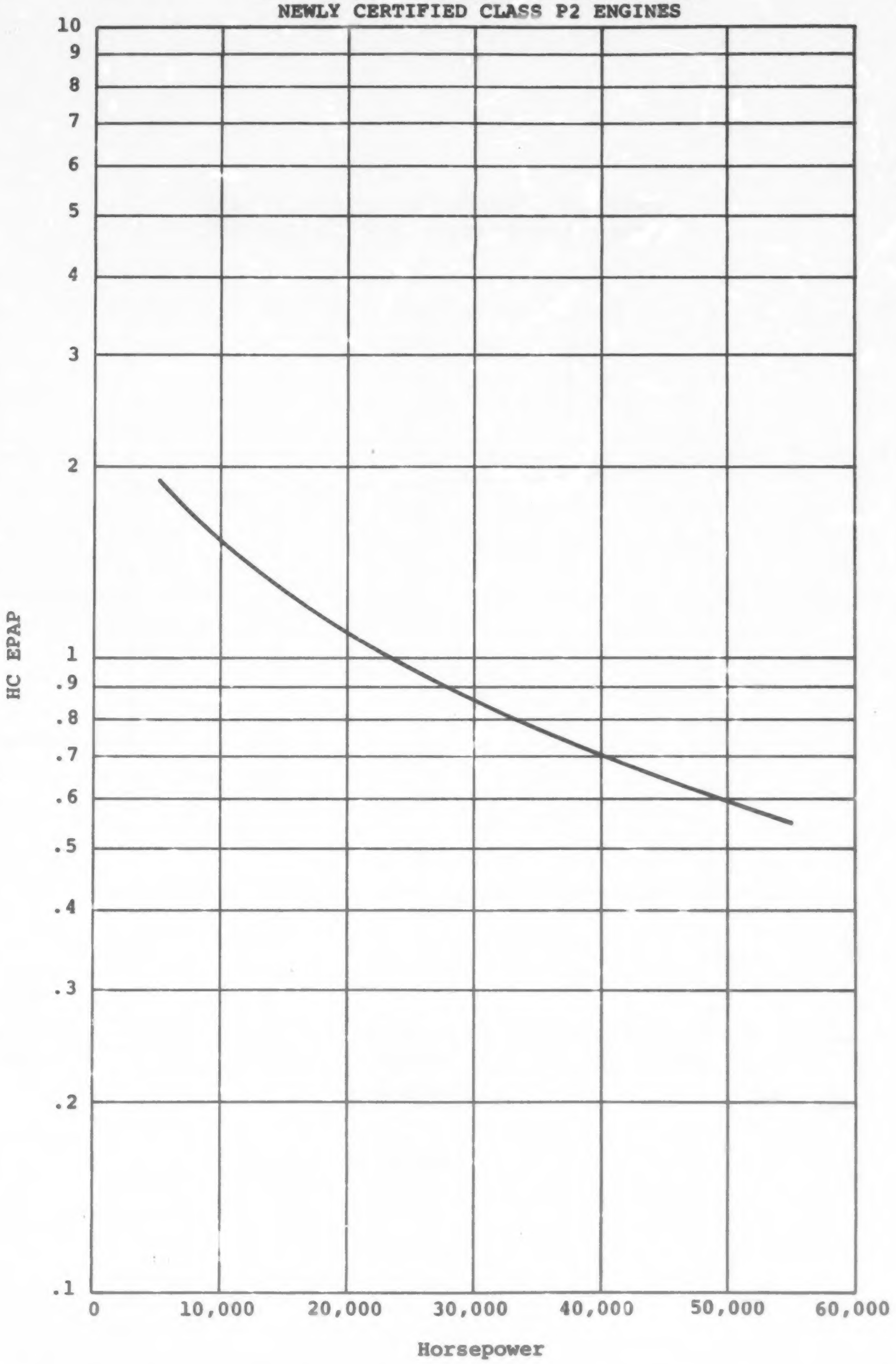


Figure 50

CO EPAP AS A FUNCTION OF HORSEPOWER
NEWLY CERTIFIED CLASS P2 ENGINES

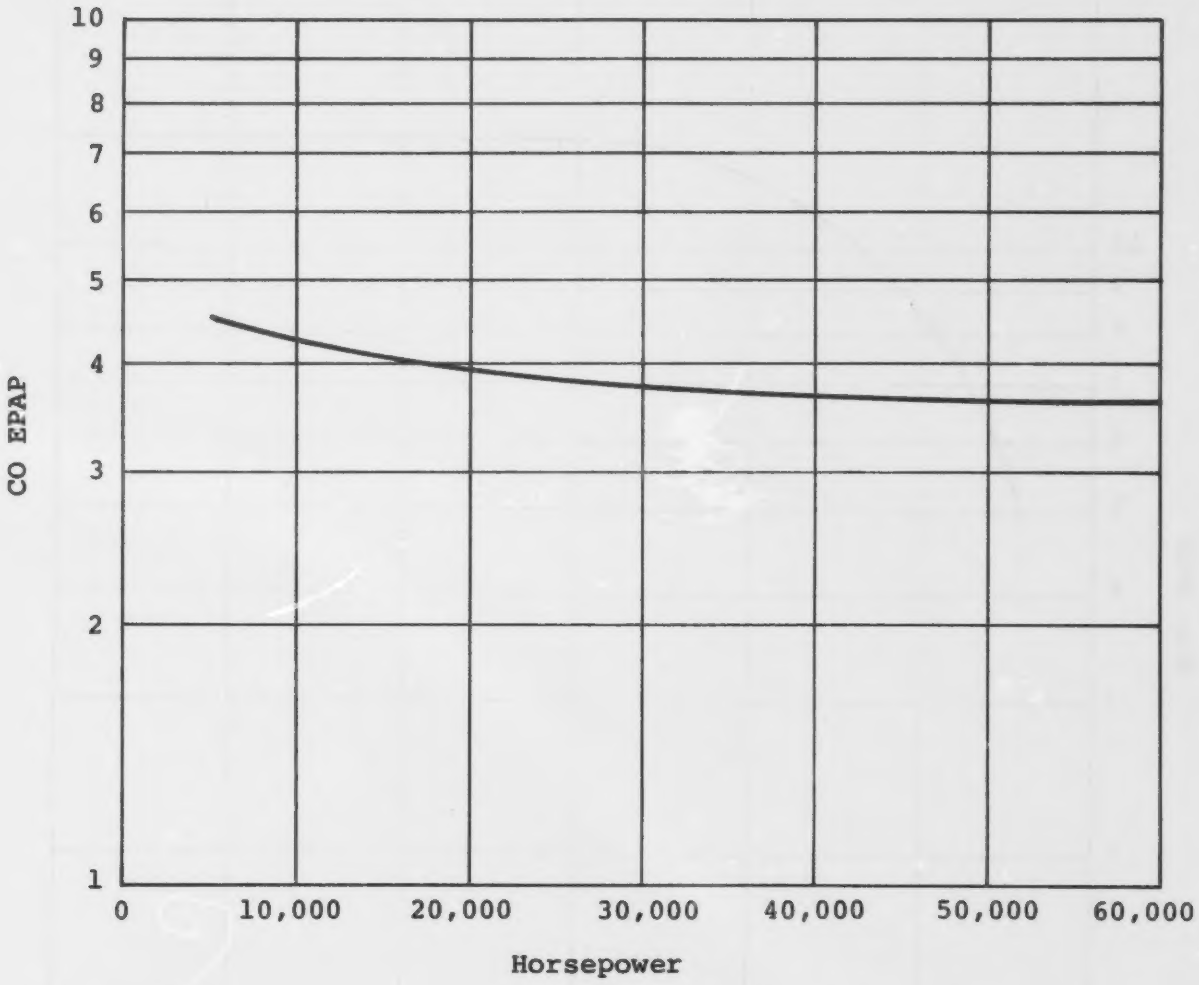


Figure 51

NOx EPAP AS A FUNCTION OF HORSEPOWER
NEWLY CERTIFIED CLASS P2 ENGINES

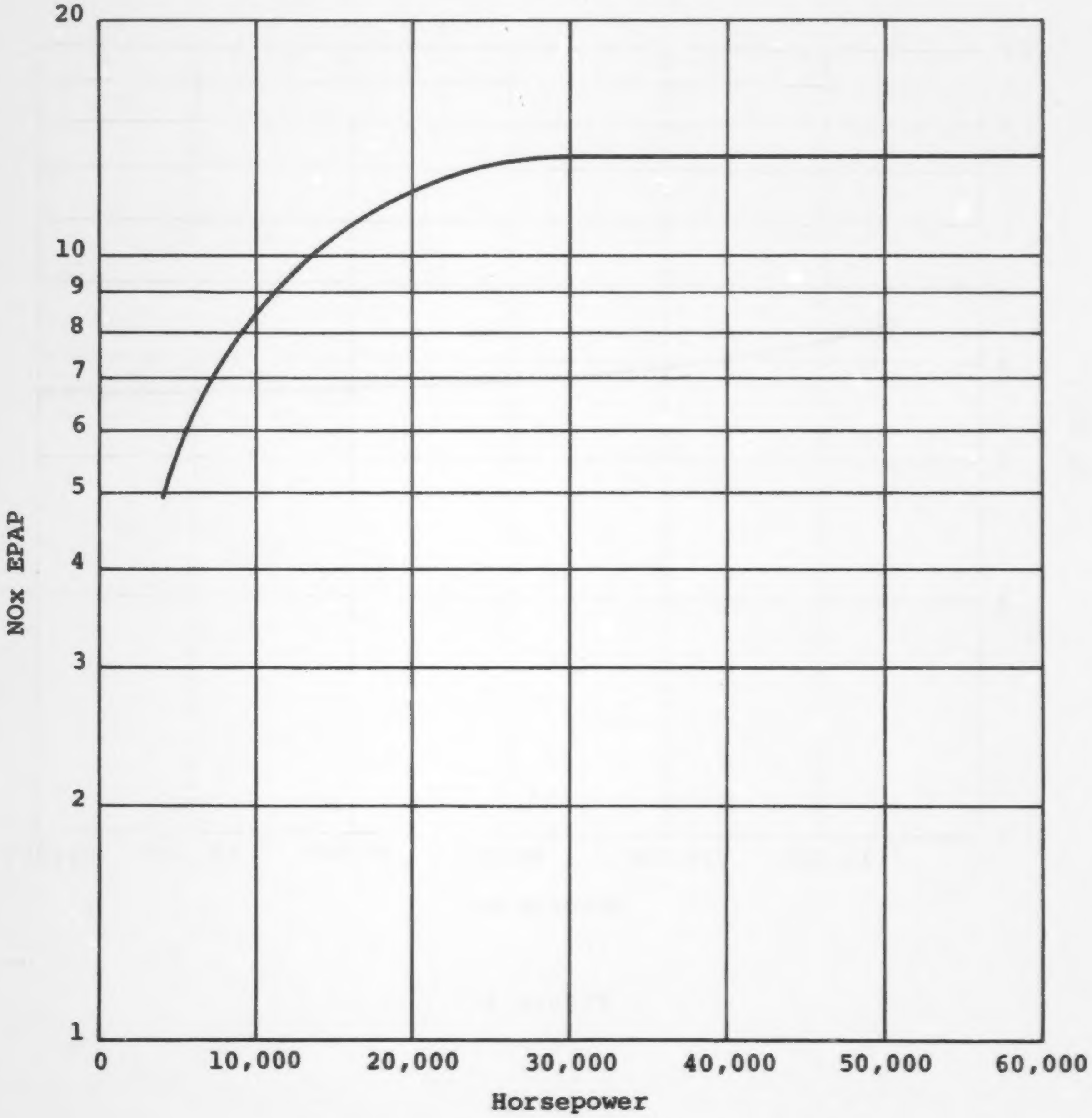


Figure 52

Section IV. Leadtime Requirements

A. Introductory Remarks

Since the regulations were first promulgated three years ago (reference 66) the engine manufacturers and NASA have been largely directing their activities and resources towards compliance with the 1979 (newly manufactured engine) standards for all four of the regulated pollutants, HC, CO, NOx, and smoke. Total success has been limited in view of the now appreciated need for some type of staged combustion system in order to substantially reduce NOx emissions without unduly compromising the other combustor design criteria. Staged combustion systems (eg., the NASA Experimental Clean Combustor Program double annular combustor applied to the General Electric CF6-50) are complex systems involving unproven design concepts (technology complexity category 3). Application in commerical use also requires economically sound design as well as safe design, thereby burdening the designer with stringent durability requirements as well as performance requirements, all of which must be met by the new concept. The manufacturers have also explored modifications to conventional designs which offer far less development risk (technology complexity categories 1 and 2), but also less capacity to control all four pollutants. Specifically, the control of NOx is largely lost although there are exceptions wherein some improvement was achieved nonetheless (but not enough for compliance). This section attempts to relate this complicated development situation to a series of time schedules, each associated with one of the established technology complexity categories of the control concepts which may be used for compliance.

In Section III, all known emissions control concepts were categorized according to their complexity of development. The categories were:

1. Little or no difficulty
2. Only minor difficulty
3. A number of difficulties to be overcome, usually with a compromise with other design criteria
4. Basic problems not resolved and are expected to be solved only with great difficulty

The fourth category is quite esoteric (e.g., catalysis) and consequently so little work has been done on methods within this group that it is not a viable alternative for compliance with any of the standards that are hoped to be implemented in the near future. As a result of this lack of sufficient time and also of the sheer lack of information, there will be no further consideration of this category here.

Each of the categories, because of their different levels of difficulty, have associated with them a typical or average compliance schedule which would apply roughly to the development of any of the control concepts in that rating. Naturally, the more complex the technology level and the control schemes within it, the longer is this typical compliance schedule. In the work that follows, these compliance schedules will be developed. However, in ascertaining a compliance date which would be reasonable for the utilization of a given rating, it is necessary to examine more than the typical schedule that is prescribed for that technology level. First, it is necessary to identify where on that schedule the different engines presently lie. Second, it is necessary to decide if the concept being developed for each engine is adequate (being complex does not guarantee it is effective) and if not, it is necessary to select an adequate concept and to re-evaluate the position of the engine on the schedule accordingly. Third, it may be necessary to revise the schedule to reflect peculiarities of a given concept or limitations of a given manufacturer which may radically alter it (recall that the schedule is only a typical or average schedule associated with that rating).

Two preliminary points should be made. First, if a set of standards are proposed based upon the utilization of a given level of complexity (e.g., category 1), it must be recognized that there may be a few engines which, for a variety of reasons, cannot comply with these standards without utilizing more complex types of control (e.g., category 2). These engines necessarily would be forced to follow the schedule of the more complex rating. In a similar vein are those engines which simply cannot comply with any set of standards employing any demonstrated techniques within each rating of technology (except perhaps for category 4 which is not available). Such engines would require an indefinite research time to continue to explore new and heretofore undemonstrated techniques. In this case, a compliance schedule cannot be readily identified.

The second point is that any schedule can be identified as either a normal or an accelerated schedule. Both types will be developed here but in view of the delays beyond the January 1, 1979 deadline that the manufacturers have claimed, the emphasis in Section V will be on the accelerated schedules.

B. Stages of a Technology Development Schedule

There are nine basic steps that occur in the incorporation of a technical concept into production. They are:

1. Concept verification
2. Combustor demonstration
3. Engine demonstration
4. Production design and procurement
5. Engine testing

6. Flight testing
7. Qualification
8. Service evaluation
9. Production preparation

C. Technology Category 2 Schedule (Normal)

The presentation below will explain the work tasks involved in each of these steps. Representative times will be given for a normal schedule for a modest technological advance (category 2). Modifications to this basic schedule for an accelerated pace, a minor technological advance (category 1), and a major technological advance (category 3) will then be discussed.

Details of the nine basic steps are as follows:

1. Concept verification. This task is considered a separate step only if the involved manufacturer is taking demonstrated technology from another source to incorporate into his engine without prior research work of his own on that approach. The purpose of this activity is to verify that the concept is functional in the combustor and has the potential for controlling emissions to the necessary level. This is not a large task; only sufficient testing is necessary here to evaluate the worth of the concept, whereas in the next step the concept must be optimized. Six months are sufficient for the analysis of existing data, planning, hardware production, and limited testing that is necessary.

A manufacturer who has undergone the exploratory development of a given concept prior to the go-ahead decision need not undergo this step at all as the necessary verification was performed in the course of the research effort.

2. Combustor development and demonstration in rig test. At the start of this task, a number of low emissions technology concepts have been applied to a combustor rig and their potential evaluated. Generally such testing does not yield configurations that are optimized with respect to emissions and engine performance. In fact, such configurations are often totally unflightworthy as well as perhaps marginal in emissions performance. Once one or two prospective candidates have been selected for further development, this task begins.

The chosen concept or concepts must be refined in the rig sufficiently to meet the pertinent standards when applied to the actual engine. Rig testing also permits extensive optimization of the system for safety and reliability. It further permits simulated altitude performance testing (including relight) which otherwise would be very costly in engine tests in altitude chambers, if possible at all.

Phase II of the NASA programs (ECCP and PRTP) involves the same sort of effort and in those programs the small engines (PRTP) are allowed 9 months for this work and the large engines (ECCP), 15 months. However, in the latter case especially, the technology involved is much more exotic (category 3) and additional time is obviously necessary. It is, therefore, reasonable to expect the requisite rig testing for category 2 technology to be accomplished in 9 months.

3. Engine Demonstration. Engine demonstration is necessary, first, to verify that the combustor, which was optimized in the rig tests of task 2, operates satisfactorily in the full engine, and second, to redesign any subsystem as necessary (e.g., the fuel control system) to achieve that satisfactory performance. This is essentially the "proof of concept" test. Satisfactory performance here means (1) acceptable steady state performance as evidenced by specific fuel consumption within production specification and acceptable turbine inlet temperature profile and (2) acceptable transient performance as evidenced by a acceleration/deceleration times within FAA requirements with sufficient surge margin. The time allotted to this task is 9 months. For comparison, the NASA programs, ECCP and PRTP, allow 15 and 12 months respectively. (Phase III). However, they involve, in their entirety or in part, more complex control schemes than are necessary for category 2 sophistication.

4. Production Design and Procurement. This task involves the design and manufacture (in limited numbers) of all the engine parts modified by the low emissions system and the associated tooling. Such engine parts may include, in addition to the combustor liner itself, the inner and outer casing, diffuser, struts, fuel control, and nozzles.

Manufacturing includes the necessary tooling as well as the limited production to supply engines for static and flight testing, qualification, and service evaluation. Proving of the tooling can be accomplished in parallel with the subsequent steps prior to commitment to production. As reported in references 44, 48 and 49 this exercise should take a little over one year, perhaps a quarter of which (design phase) can easily overlap the engine demonstration period as the production configuration is finally identified.

5. Engine Testing. This activity involves endurance and cyclic testing necessary first to generate an adequate safety record for later flight testing and engine qualification and second to develop a maintenance and reliability record for service. Typically about one year is necessary before sufficient time is accumulated to begin flight tests as reported by General Electric and Rolls Royce in references 8, 48,and 45. This type of testing, however, usually continues throughout the production life of the engine.

6. Flight Testing. This is done primarily to investigate engine performance at altitude. It is usually done on a corporate owned experimental aircraft or an available military aircraft neither of which are subject to the FAA requirements of certification. Included in the engine performance criteria are thrust, specific fuel consumption, relight, and transient behavior. Environmental factors such as icing,

etc., may be investigated as necessary. The T2 class engine manufacturers generally allocate about three to six months to flight testing prior to the start of qualification (references 8 and 48) while the T1 and P2 class engine manufacturers apparently often get by with less, perhaps three months (references 4 and 33).

7. Qualification. This step involves obtaining the necessary type certificate, supplemental type certificate, or engineering approval for the low emissions engine. The amount of effort involved here is largely dependent upon the type of certification necessary. In any case, FAA certification involves mostly paperwork as a large part of the necessary testing has already been done. Following the recommendation of several of the manufacturers (references 8, 14, 33, 45, and 48), three to six months are delegated to this task.

8. Service Evaluation. Once an engine has the necessary FAA certification or approval, it is, strictly speaking, available for public use. Nonetheless, another stage of testing, that of service evaluation, has developed as a matter of industry policy prior to full production. The procedure in service evaluation is to have a limited number of engines installed on fleet aircraft (one per plane) for a long enough period of time to judge their performance, reliability, and maintainability in actual use. While reliability may be considered a safety issue (the FAA considers service evaluation a vital supplement to its own required testing for certification), it is intended primarily to prove the economics of the engine in service. The length of time of the service evaluation depends upon the rate at which flight time and landing-takeoff cycles are accumulated in service and the extent to which the new system differs from the old (an exotic system will be scrutinized more thoroughly for reliability). A system which has had a history of difficulty in development will also command a longer service evaluation.

At least one manufacturer had earlier indicated that a one year service evaluation would be adequate for its engines (reference 4). This is a fairly short time, giving a high time of perhaps 3500 hours and 1400 cycles for commercial engines and somewhat less for general aviation engines. However, this is supported by reference 26. It should be pointed out, on the other hand, that some service evaluations take longer; for instance, the JT8D and JT3D smoke retrofit programs service evaluations took 1 1/2 to 2 years to complete. However, both represented attempts to install advanced technology in quite mature engines (can and can-annular combustors) and both experienced a history of development problems. A similar situation can be expected to occur with the Allison 501D (P2 class), another very mature engine.

There are, however, two more points that must be weighed. First, the large commercial engines classes, while of fairly recent origin, are accumulating flight time very rapidly and by the time the new combustors are ready for production, these engines will themselves be "mature" (10-12 years old) so that the airlines will be expecting a high level of durability. Second, as these large engines will dominate the fleet and all may eventually be affected by the standards (because of the proposed retrofit requirement), it follows that any failure to perform satisfactorily may have a considerable economic impact on the airlines. For these reasons, the airlines contend that an adequate service evaluation should not be compromised. Any lost time would eventually be compensated for by the proposed retrofit program. Following recent industry recommendations (references 28, 40, 44, 45, 48, and 49), two years are allotted for commercial engines for the service evaluation. The airlines involved in the service evaluation should be encouraged to see that the two year period is used to the maximum advantage. Failure to put the greatest possible time on the engines in service evaluation may lead to the acceptance of a system with hidden flaws which would eventually prove unreasonably costly to the airlines.

For general aviation a problem arises in that the annual usage rate is generally far below that of the commercial engines. This means that in a given period, considerably less time can be put on the engines. This is compensated for by the less stringent durability requirements of private operators. A one year service evaluation is generally considered adequate for the T1 and P2 classes by the industry (references 4 and 32) with the exception of General Motors which produces a very mature P2 class engine (the Allison 501D) achieving a very high durability performance. This single engine should be treated as a special case, if necessary.

9. Production Preparation. The manufacturers (eg. reference 45) have called for a one year lag between the end of the service evaluation and the actual production on the basis that they do not wish to commit to final tooling, etc., until the final validation is in (the service evaluation). An earlier commitment in effect foreshortens the service evaluation as the "go-ahead" decision must be made before the service evaluation is concluded.

This normal schedule for category 2 control schemes is summarized below in figures 53 and 54.

D. Technology Category 1 Schedule (Normal)

It is next necessary to determine the changes from this schedule that would occur with the utilization of technology from another technology complexity category. First, a normal schedule for category 1 technology is reviewed.

1. Concept verification. This task can be performed quite speedily in view of the generally small amount of analysis and hardware development needed to begin testing. Three months is adequate.

2. Combustor rig development. By definition, there are no category 1 concepts which materially affect the combustor. Therefore this step is drastically reduced and constitutes little but verification, where necessary, that any new components do not adversely affect the combustor performance (which is unlikely in view of the character of the control schemes). In some cases, this step can be deleted entirely (eg., increased idle speed). Again, three months is sufficient.

3. Engine demonstration. The importance of this phase of the schedule for category 1 technology depends significantly upon the particular control concept involved. Engine testing for a fuel sectoring concept is much more important (to check turbine wear) than it is for an increased idle concept in which case there is no change in the engine or its performance. In any event, engine testing is of generally less importance for category 1 control as there are generally no significant effects on the engine at power levels above idle. Three to six months is all that is warranted here.

4. Production design and procurement. Again, this task is often considerably reduced because of the limited nature of the changes to the engine involved in most category 1 technology. The major exceptions to this are the external air-assist concept and possibly airbleed in some applications. This task should take from three to nine months, depending on the concept involved with still three months overlap with the third task, as before.

5. Engine testing. While one year's worth of testing may be desirable for the air-assist concept, it is hardly necessary for the other concepts of category 1, one-half that time is ample and even superfluous in certain situations such as the increased idle speed concept. Generally three to six months should be acceptable with special consideration being recognized as necessary for development of the air-assist concept. For comparison, AiResearch (reference 14) suggests one year for all engine testing prior to certification (Task 3 and 5).

6. Flight testing. Once again the amount of time devoted to this effort depends largely upon the concept involved, but it is probably sufficient to devote to this the lower limit of the time that was devoted to flight testing of category 2 technology, namely three months.

7. Qualification. There is little reason for change here. In the case of increased idle speed, both steps 6 and 7, flight testing and qualification, become trivial exercises requiring a minimal amount of time.

8. Service evaluation. As the purpose of the service evaluation is to determine through actual usuage the maintainability and performance of the modification in question, then for category 1 technology wherein the control concepts usually have little or no effect on the engine performance only a minimal service evaluation is required, ranging from nothing to one year. The one year figure would apply to the air-assist concept for which the questions of durability, etc., must be addressed.

9. Production preparation. This stage would not generally be necessary for most category 1 concepts, but would be required on the normal schedule for air-assist and airbleed if changes have been made to the original hardware in the latter case. Depending upon the control concept in question, zero to six months should be allotted to this.

This normal schedule for technology category 1 control schemes is summarized below in figure 55.

E. Technology Category 3 Schedule (Normal)

Next, a normal schedule for category 3 technology is reviewed.

1. Concept verification. The nature of this task is not appreciably different from that for category 2 technology so that the six month time is adequate here also.

2. Combustor rig development. The time frames of the Phase II parts of the NASA programs (ECCP and PRTP) are relevant for category 3 as indicated in the discussion earlier. Thus for large engines 15 months is necessary and for small engines, 9 months.

3. Engine demonstration. Again the NASA programs (category 3) set the pace, 15 months for T2 class engines and 12 months for the T1 or P2 classes.

4. Production design and procurement. No change from the category 2 situation appears warranted.

5. Engine testing. Probably no change from the category 2 situation is necessary, but in light of the complex fuel control which is required (doubly so if staging must be performed in flight as with the GE double annular combustor), additional engine testing may be warranted. This would then require 18 months for this task.

6. Flight testing. In view of the major engine changes the full six months should be used prior to qualification.

7. Qualification. No change. FAA qualification is fundamentally the same: The hardware at this point has proven itself.

8. Service evaluation. The two year service evaluation recommended by the industry is still acceptable in this case although it is quite likely that problems will arise with such exotic systems in use which will then require modification to the system, testing, and further service evaluation. Therefore, it is quite plausible that a three year period is warranted for this service evaluation.

9. Production preparation. No change from the category 2 time is needed.

The normal schedule for technology category 3 technology development's summarized in Figure 56 and 57.

F. Accelerated Schedules

It is now necessary to investigate accelerated schedules, ones in which some risk is assumed that if unexpected problems develop, the impact or the schedule and on the cost is magnified considerably. The following remarks apply to all of the schedules discussed above. Accelerations in a schedule will be given as a percentage of the normal schedule times.

1. Concept verification. For those manufacturers who must go through this step there is not any easy way to avoid part of the work. What is not done here (analysis, rig hardware manufacturing) must then be done in step 2. Consequently, all the manufactuere can do is to push for overtime, shop priority, etc. Total savings may be 20%.

2. Combustor rig development. The NASA (category 3) times are quite long for what is the required minimum effort for they are based upon the refinement of at least two different approaches. For those manufacturers who have not yet conducted this task for one of their engines, the NASA experience will be highly beneficial and much otherwise wasted effort can be avoided by careful attention to the lessons of the NASA ECCP and PRTP. For category 3, the savings may be 33%, while for the other categories, perhaps 20% savings can be expected through overtime, shop priority, etc.

3. Engine demonstration. Although NASA has allocated 15 months for Phase III, it is worthwhile to note that the actual JT9D engine demonstration is to be completed approximately 10 months after start of the contract although the report will come out somewhat later. Considering this as a guideline as to the pace that can be achieved if there are no hold-ups, it can be expected that an accelerated schedule here for category 3 might save 33% again. For the other ratings, the same 20% savings perhaps can be expected for reasons of overtime, etc.

4. Production design and procurement. While the usual acceleration can be achieved (20% savings) through high priority treatment of the project, further gains can be made by overlapping the engine demonstration phase by as much as 50% rather than the nominal 33% (at the risk of wasted effort if there is failure).

5. Engine testing. Through priority treatment, this task can easily be cut in half (savings of 50%).

6. Flight testing. Probably the best that can be expected here is the lower limit of what the manufacturers have indicated they allow, namely three months. Some acceleration may be possible, but safety considerations in flight as well as the preparation for qualification to follow weigh against this.

7. Qualification. This is essentially in the hands of the FAA: Little time can be gained here from the manufacturers' effort. It is reasonable to expect, however, that timely preparation of the material by the manufacturer and expedited handling by the FAA should keep this time to the minimum normal (3 months).

8. Service evaluation. Service evaluation can always be foreshortened, but at the expense of completeness of testing. There is no way to have the same duration of testing in a shorter period as the engines are used in airline service and there is no way to accelerate

their usage. A shorter evaluation may lead to later problems as happened in the JT8D smoke retrofit program, especially if category 2 and 3 technology is being employed. The service evaluation for category 1 technology is already minimal. At best, for category 2 and 3 technology a 25% savings can be hoped for if no problems arise during the evaluation. Even then later problems may plague the airlines until final corrections are made.

Of course, in the extreme, no specific service evaluation is required as is the case with a new engine. The initial experience in using the engine in essence becomes a service evaluation. There is, naturally, a resultant economic penalty. However, this extreme is not assumed for the accelerated schedule.

9. Production preparation. For category 1 technology, this step is not long enough (3 months) to warrant attempts to shorten it. For technology category 2 and 3, however, some savings could be realized if the task were shortened by 25% and moved up so that it would begin six months prior to the end of the service evaluation. However, as noted in the first discussion on scheduling, an earlier commitment in effect foreshortens the service evaluation as the "go-ahead" decision must be made before the service evaluation is concluded.

To compensate, if the airlines ensure the greatest possible in-service time on the test engines, the probability of later rejection is vastly diminished. Furthermore, with sufficient motivation, the manufacturer can tool for production in less than one year, especially as some tooling from the manufacture of the service evaluation test engines is available along with the necessary designs. If a total of nine months is taken for the production preparation and if this phase is begun three months prior to the end of the service evaluation, then only six months beyond the end of the service evaluation is necessary before production begins.

An alternative point of view which can be taken by the industry is that a fixed period be allotted for service evaluation and preparation for production. It is the industry's decision (manufacturers and airlines) to agree among themselves upon the best breakdown between service evaluation time and production preparation time. Such a flexible procedure, of course, allows the industry to minimize its cost within the given constraint.

Figures 58-62 describe graphically the accelerated schedules for the three categories of technology under consideration. These schedules, while optimistic (allowing for no major setbacks), are realistic. In this regard, the following remarks are relevant from material submitted to the EPA in response to the NPRM of December 12, 1972, proposing air pollution standards for aircraft and aircraft engines (FR, Vol. 37, No. 239).

1. For the time required to go from concept identification through engine demonstration (1 year, 8 months by Figure 60 or 2 years, 1 month by Figure 62):

Aerospace Industries Association - "It can be conservatively estimated that at least eighteen (18) months are required to design, fabricate hardware and conduct sufficient full scale engine testing to determine, by further development, the useable potential of promising rig-developed combustor designs or concepts."

Pratt and Whitney Aircraft - "It can be conservatively estimated that at least two (2) years are required to design, fabricate hardware and conduct sufficient full-scale demonstration engine testing to determine, by further development, the useable potential of promising rig-developed combustor designs or concepts."

2. For the time required to deliver the first production engine once production design has been initiated (3 years, 1 month by Figures 60 or 4 years, 1 month by Figure 62):

Aerospace Industries Association - "Typically there is a four year lead time required to develop an aircraft gas turbine engine from the initiation of engineering drawings until the first production engine is delivered."

Pratt and Whitney Aircraft - "Past history has shown that it takes at least four (4) years from design initiation through completion of the certification testing to the delivery of the first production engine."

General Electric - "With regard to implementation dates, it should be noted that several years of design, development, evaluation and preproduction effort are normally required to provide an acceptable combustor for use in a given engine application. Typically, this time span ranges from three to four years."

G. APU Schedules (Normal)

Generally APUs, like the propulsion engines, must be flightworthy as they are to be used as auxiliary power backup in flight. This means that the development times will largely parallel that of the P2 class with the notable exception that a lengthy service evaluation is not required: Durability and maintenance of optimum performance of APUs are not pursued by the users in view of their relatively small impact on the total fuel consumption and maintenance burden. Furthermore, APUs are not stressed and cycled in the same fashion as is a propulsion engine. In view of these considerations, the compliance schedule for APUs would differ from that for the propulsion engines as follows:

APU Technology Category 1 and 2 Technology Schedules

2. Combustor rig demonstration. In view of the less stringent requirements on the APU noted above, this task need not spend as much time on performance development as is necessary for propulsion engines. A 33% savings can be realized.

3. Engine demonstration. The remarks made relative to step 2 are applicable here also.

5. Engine testing. The less stringent requirements on APUs would lead to less need for this testing; a 50% time savings is possible.

6. Flight testing. This is necessary only for those engines which have an in-flight function, but again, as reliability and maintainability do not have the importance they have in propulsion engines, a 50% savings in time may be effected.

8. Service evaluation. As indicated above, a lengthy service evaluation is not required. In fact, for the modest changes involved, the service evaluation is largely unnecessary.

The other steps that have not been addressed here remain unchanged: They require the same time for both the propulsion engines and the APUs. Figures 63 and 64 present the normal APU schedules for category 1 and 2 technology.

APU Technology Category 3 Technology Schedule

Although the performance and service requirements on APUs are not usually so strict as on propulsion engines, not too much opportunity is offered by this fact to shorten the development schedule for the application of category 3 technology into APUs. This is so because incorporating this technology into APUs has a number of difficulties unique to the APU environment that would require special developmental effort. Specifically, the combustor operating conditions and the combustor size together create a situation in which much of the category 3 technology, especially that which effects NOx control, is ineffective or physically difficult to implement. Therefore, the schedule is likely to follow that for propulsion engines except for step 8, service evalution.

8. Service evaluation. Because of the radical changes, an APU employing category 3 technology should be expected to undergo some sort of service evaluations although not necessarily to the extent of propulsion engines. Somewhat arbitrarily, a six month period is allotted for this task.

Figure 65 presents normal schedule for the implementation of category 3 technology into APUs.

H. Accelerated APU Schedules. There is no reason why accelerated schedules here should differ in character from those for propulsion engines. Hence, those percent savings are assumed to apply and figures 66, 67, and 68 summarize the accelerated APU schedules for the three technology categories.

I. Schedules for Newly Certified Engines

It is assumed that any standard for newly certified engines will be based upon the use of at least category 3 technology in order to achieve effective NOx control without the use of water injection. The schedule then should be roughly the same as that which applied to newly manufactured engines with the exception that a service evaluation is not required here. A service evaluation is a practice which has been established to provide a measure of the economic impact to the airlines, resulting from equipment modifications. This knowledge, is quite important to the airlines as older engines have established high levels of durability and maintainability which make their operation very economically attractive. Any change in the engine is expected, or at least, hoped to preserve that economic performance. In the case of a newly desiged engine there is no prior performance record; the introduction into service and the initial experience constitute the baseline economic performance record which is a service evaluation of sorts.

In addition, it is reasonable to expect that if there is an engine now in development which is expected to be certified after the January 1, 1981 date specified in the existing regulations, that program has incorporated category 3 technology into its combustor development effort. As that technology development has nearly reached the production design stage (i.e., NASA ECCP), it follows from Figure 57 that newly certified engines utilizing category 3 technology (NOx control) could be available by January 1, 1981. For this estimate a normal schedule has been assumed as it is unlikely that development of a full engine could proceed at any faster pace.

TECHNOLOGY CATEGORY 2
T2 CLASS ENGINES
NORMAL SCHEDULE

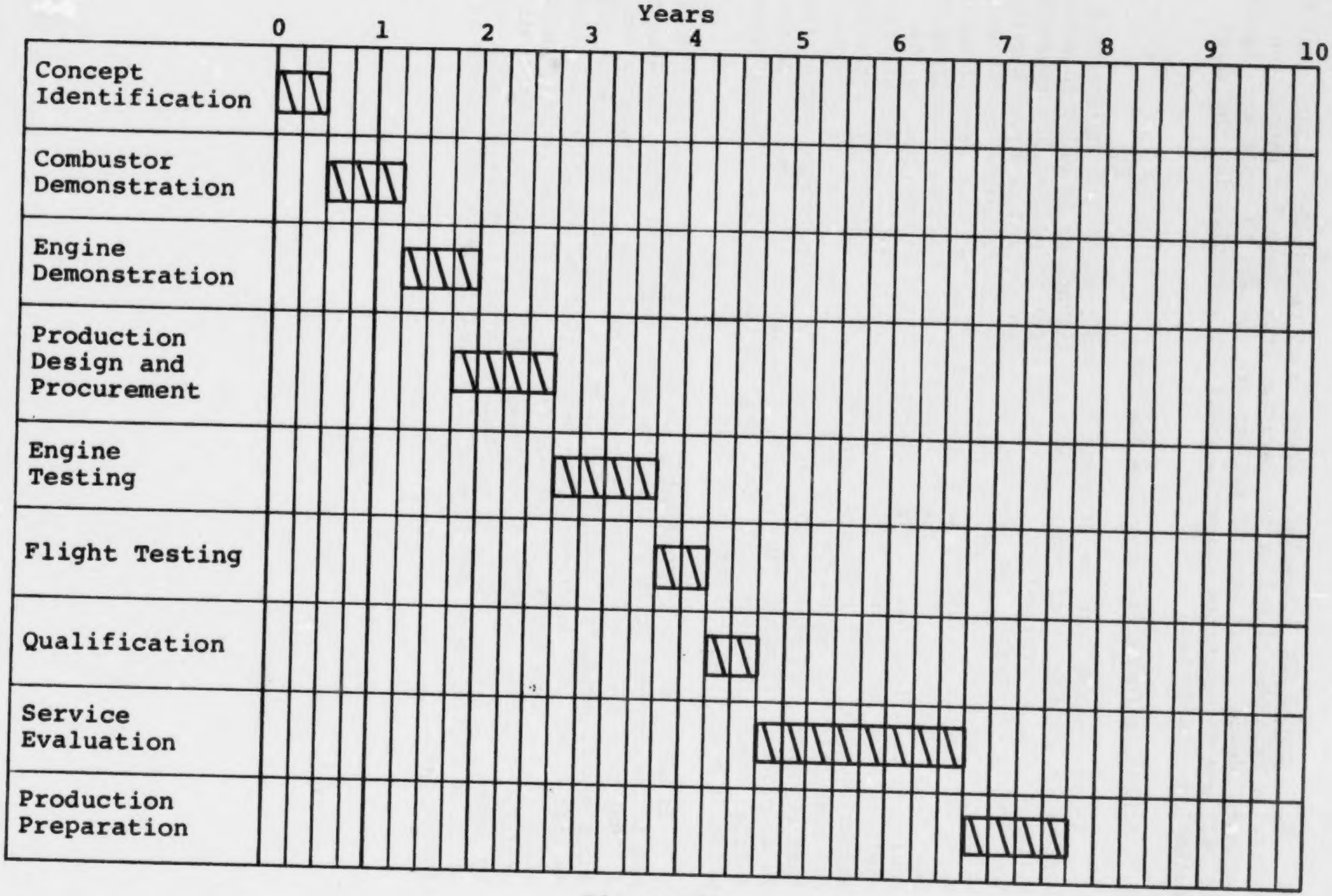


Figure 53

TECHNOLOGY CATEGORY 2
T1 & P2 CLASS ENGINES
NORMAL SCHEDULE

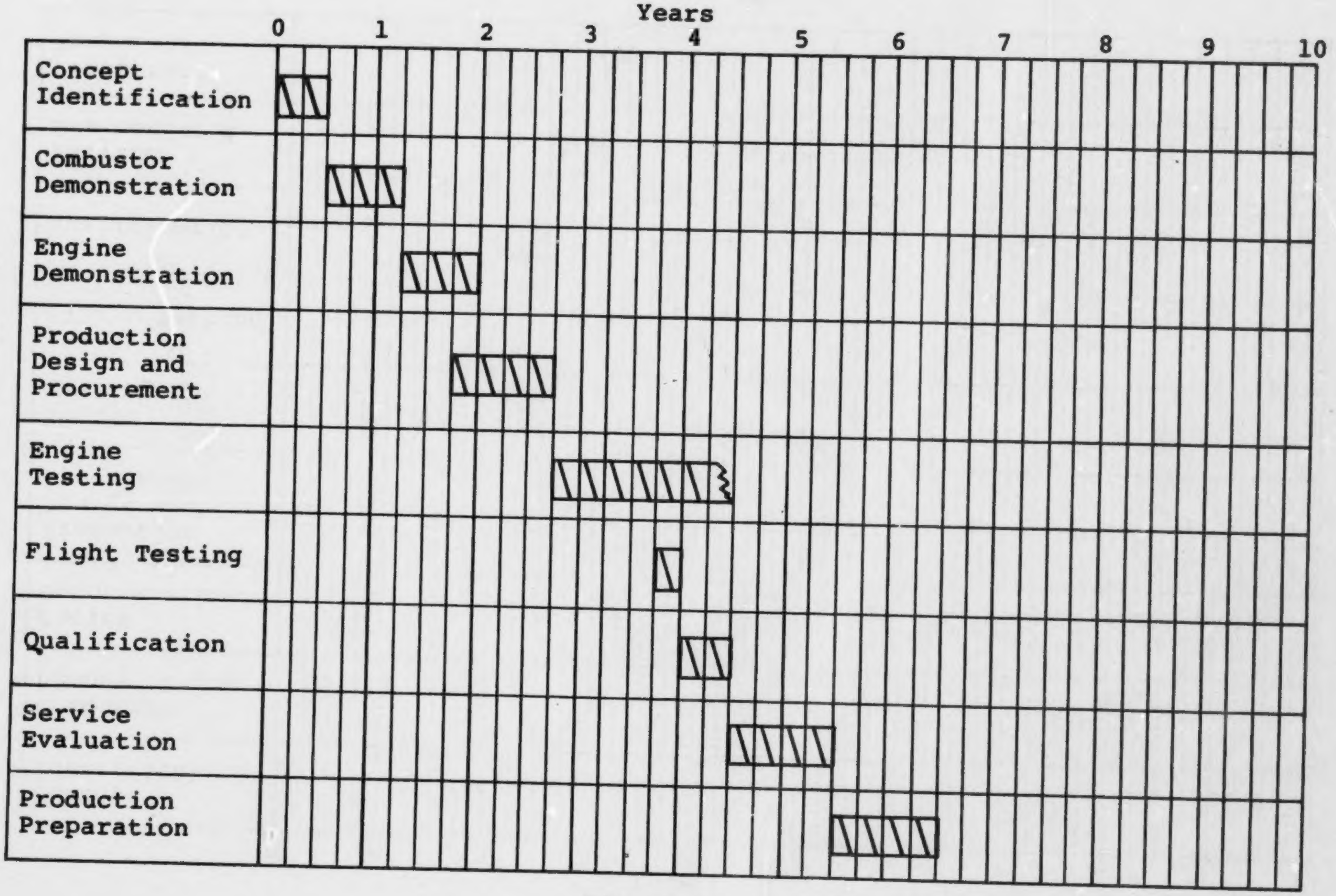


Figure 54

TECHNOLOGY CATEGORY 1
CLASS T1, T2 & P2 ENGINES
NORMAL SCHEDULE

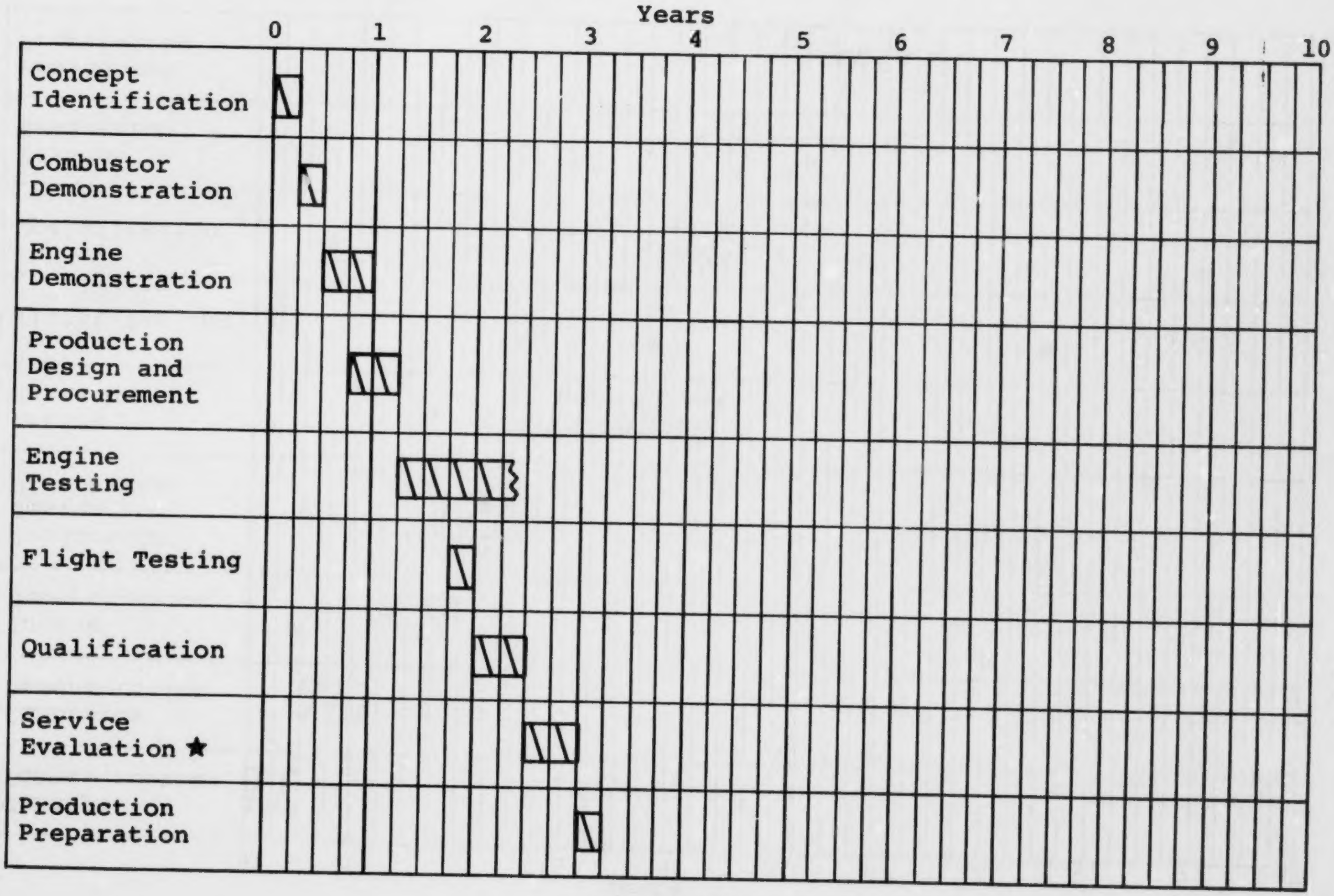


Figure 55

★ One year service evaluation is required for the air-assist concept

TECHNOLOGY CATEGORY 3
T2 CLASS ENGINES
NORMAL SCHEDULE

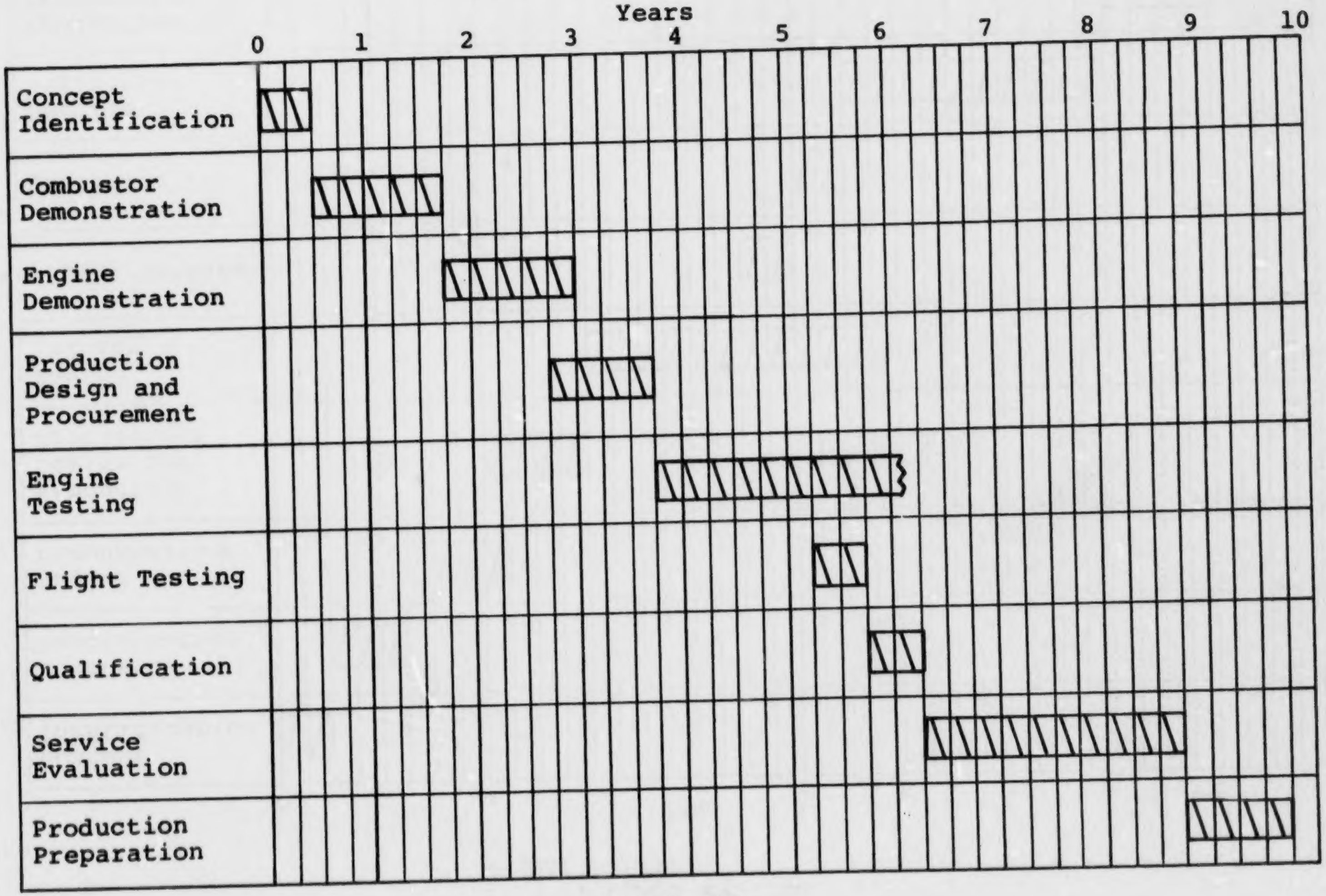


Figure 56

TECHNOLOGY CATEGORY 3
T1 & P2 CLASS ENGINES
NORMAL SCHEDULE

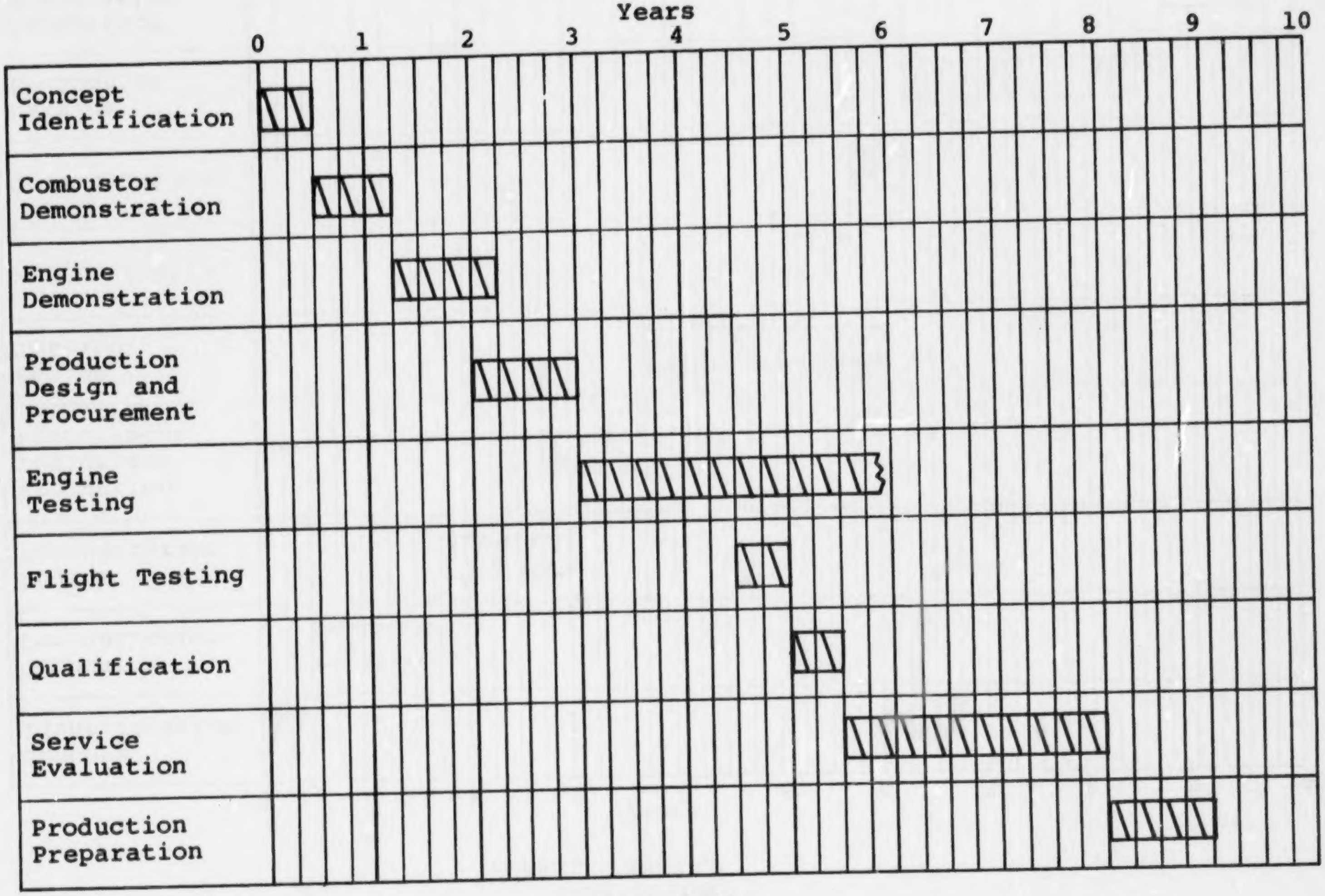


Figure 57

TECHNOLOGY CATEGORY 1
CLASS T1, T2 & P2 ENGINES
ACCELERATED SCHEDULE

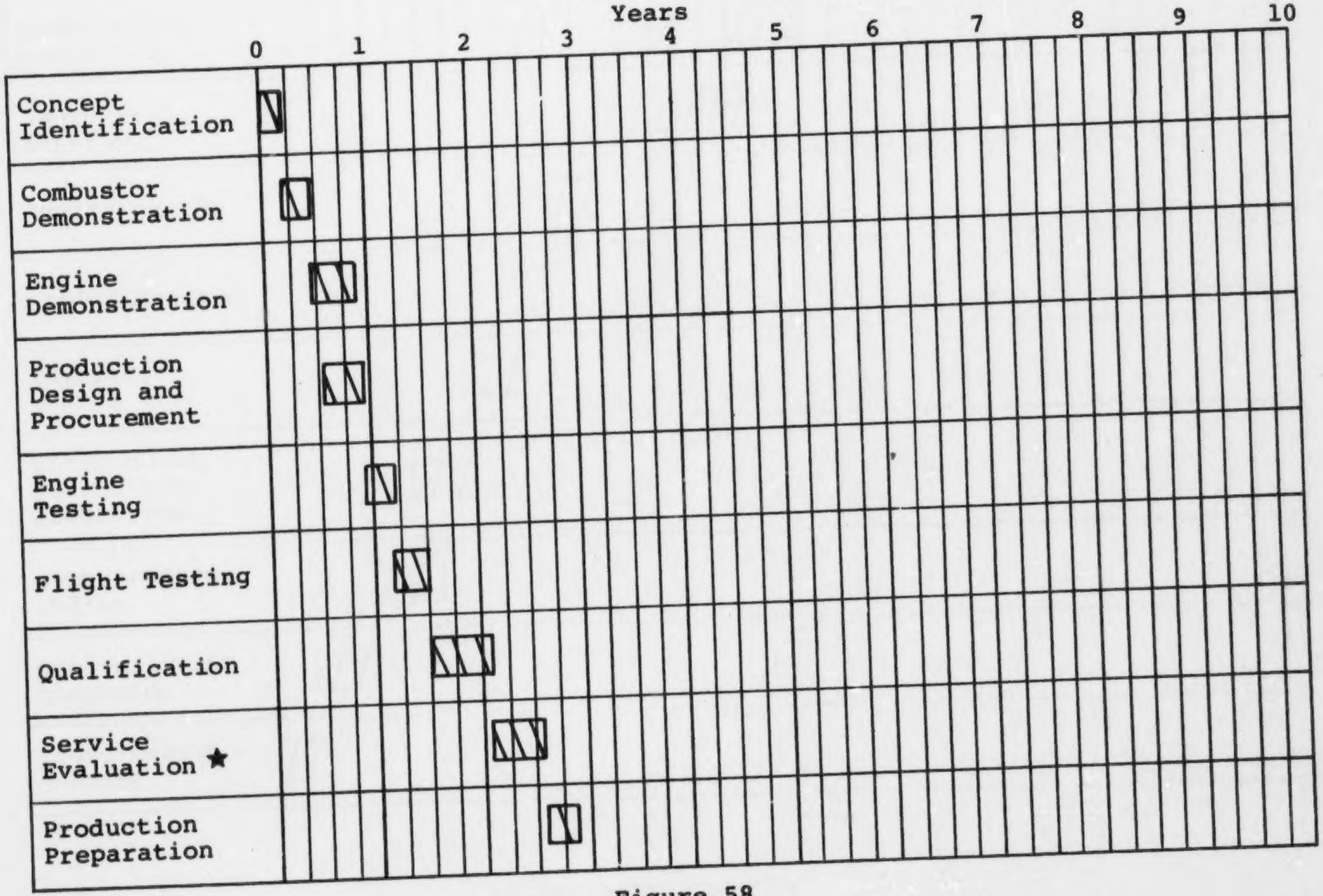


Figure 58

★ One year service evaluation is required for the air-assist concept

TECHNOLOGY CATEGORY 2
T2 CLASS ENGINES
ACCELERATED SCHEDULE

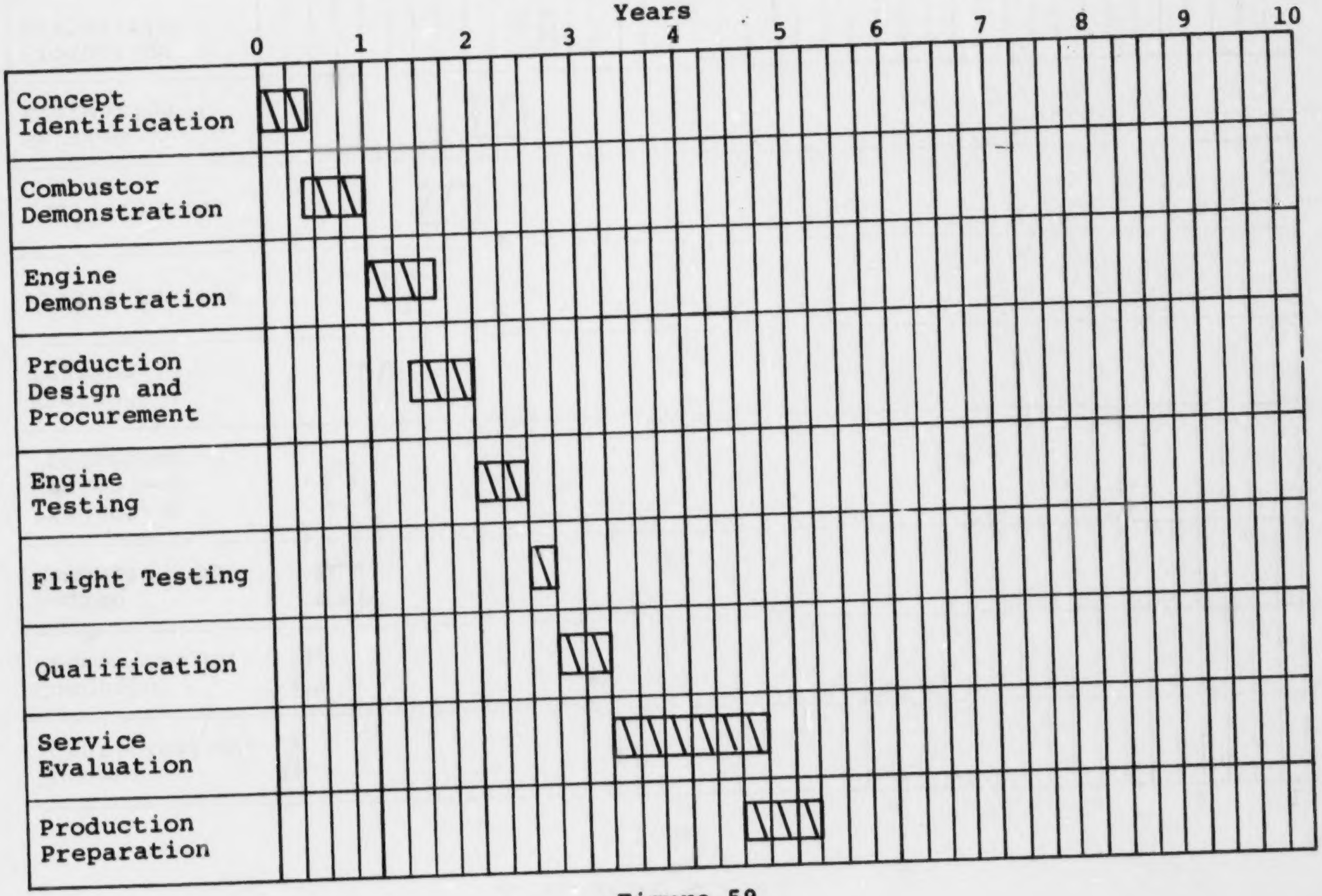


Figure 59

TECHNOLOGY CATEGORY 2
T1 & P2 CLASS ENGINES
ACCELERATED SCHEDULE

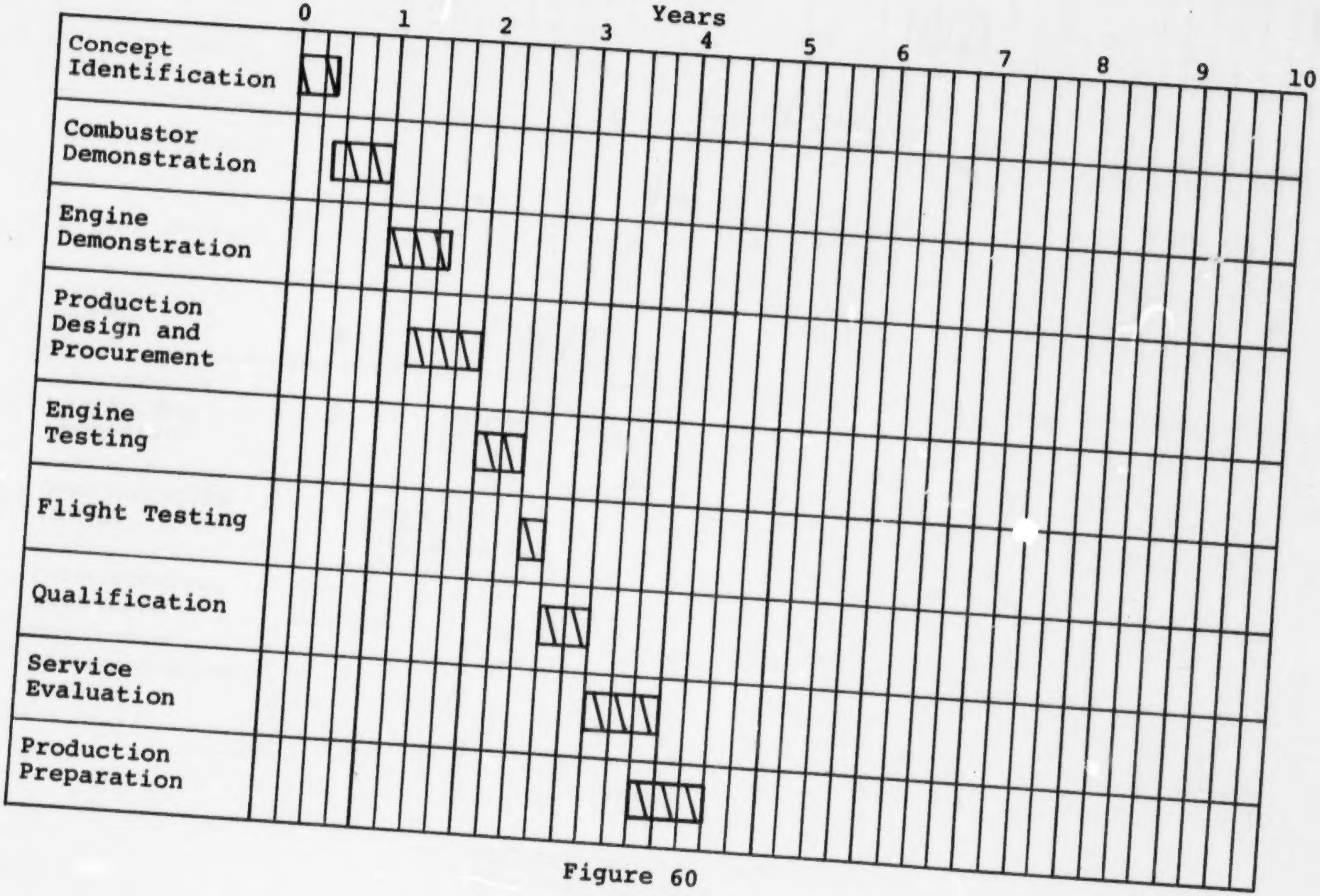


Figure 60

TECHNOLOGY CATEGORY 3
T2 CLASS ENGINES
ACCELERATED SCHEDULE

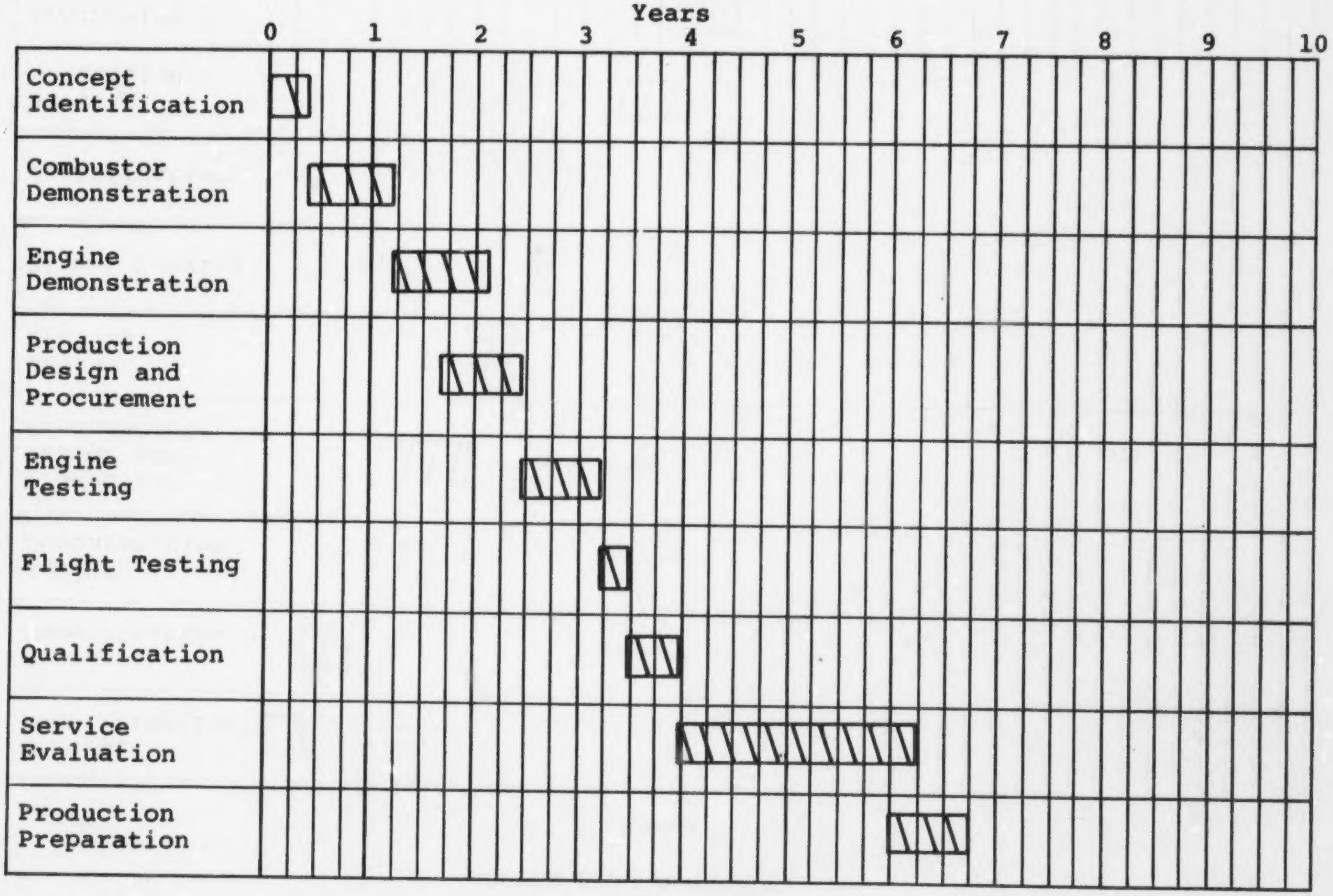


Figure 61

TECHNOLOGY CATEGORY 3
T1 & P2 CLASS ENGINES
ACCELERATED SCHEDULE

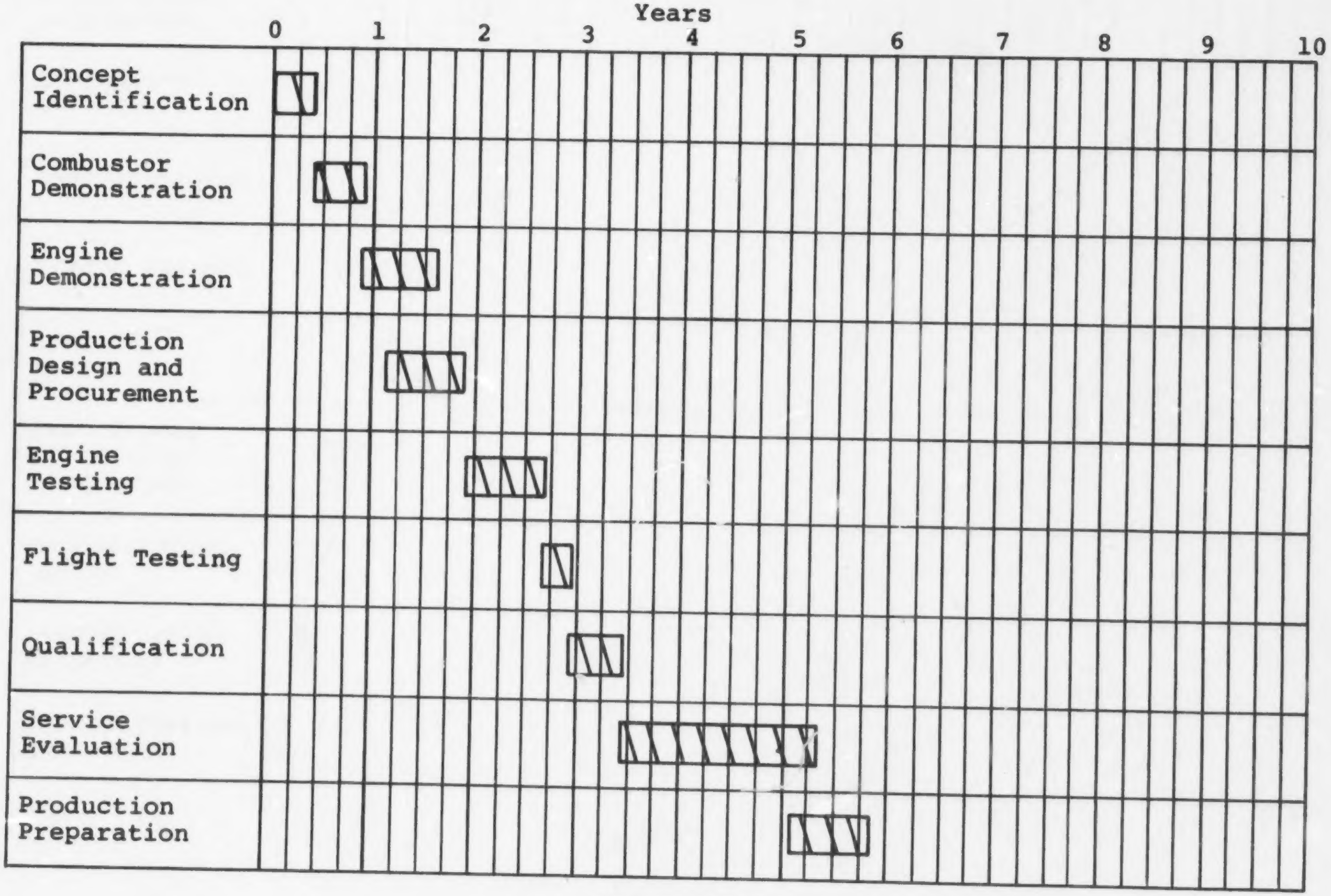


Figure 62

TECHNOLOGY CATEGORY 1
APU
NORMAL SCHEDULE

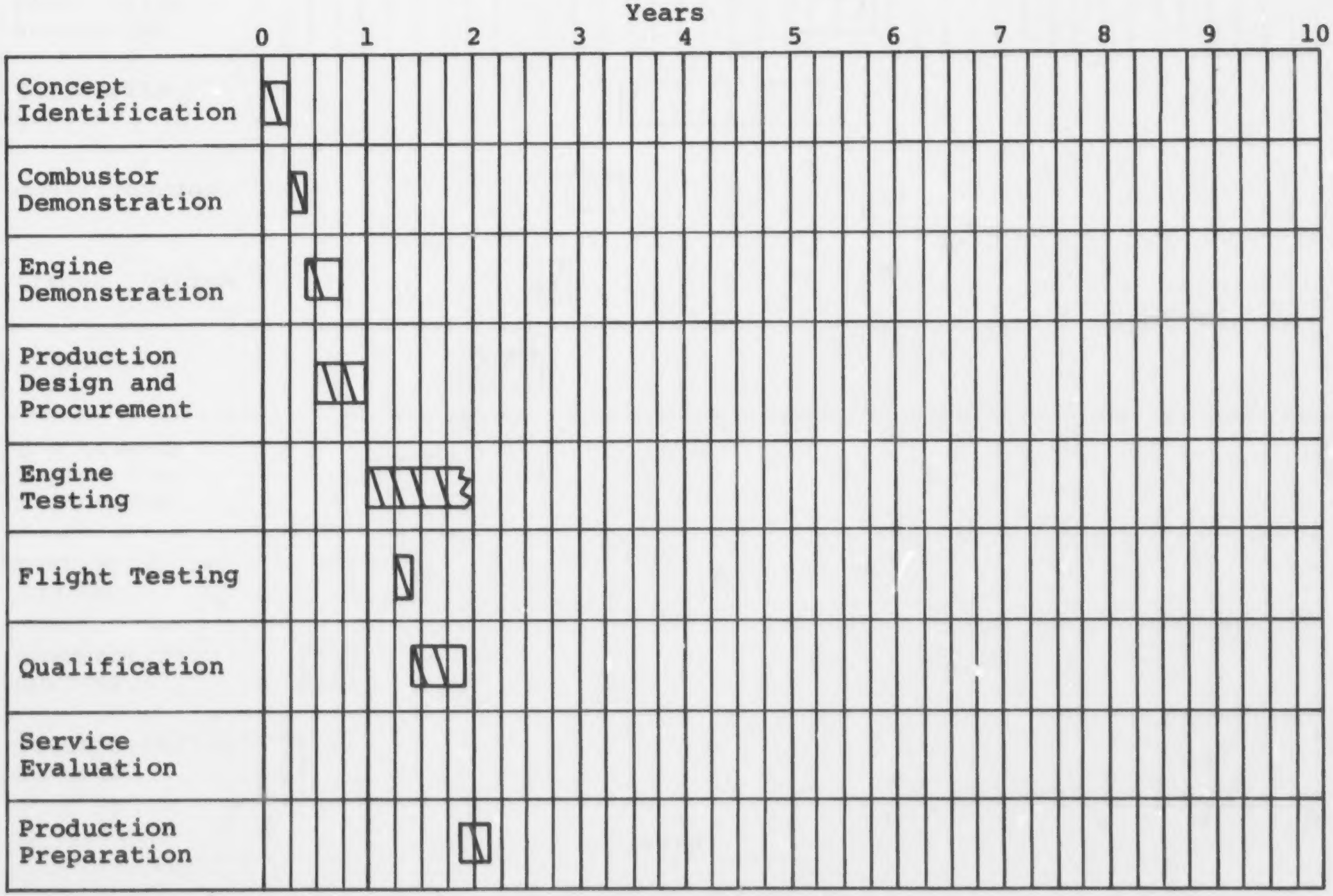


Figure 63

TECHNOLOGY CATEGORY 2
APU
NORMAL SCHEDULE

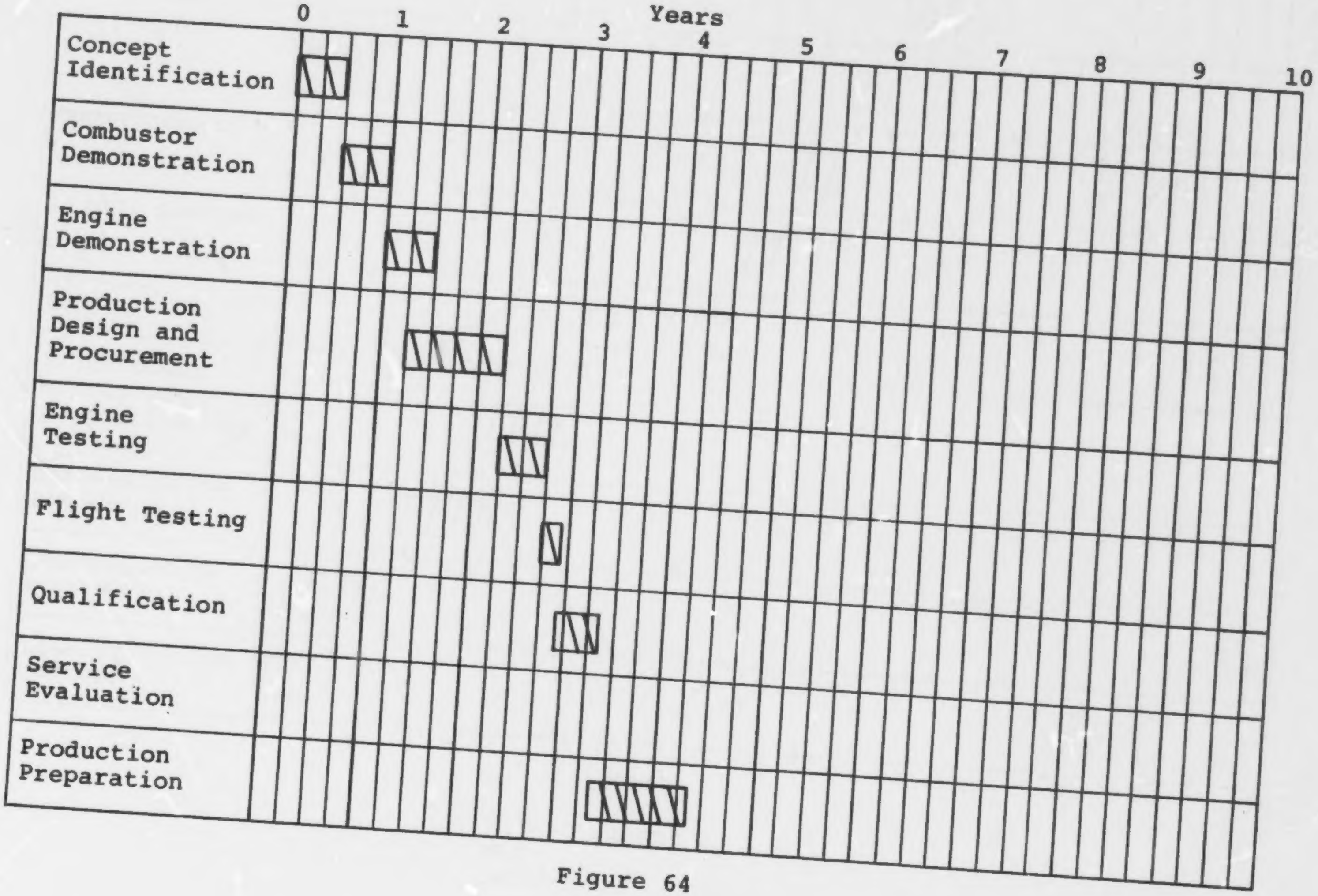


Figure 64

TECHNOLOGY CATEGORY 3
APU
NORMAL SCHEDULE

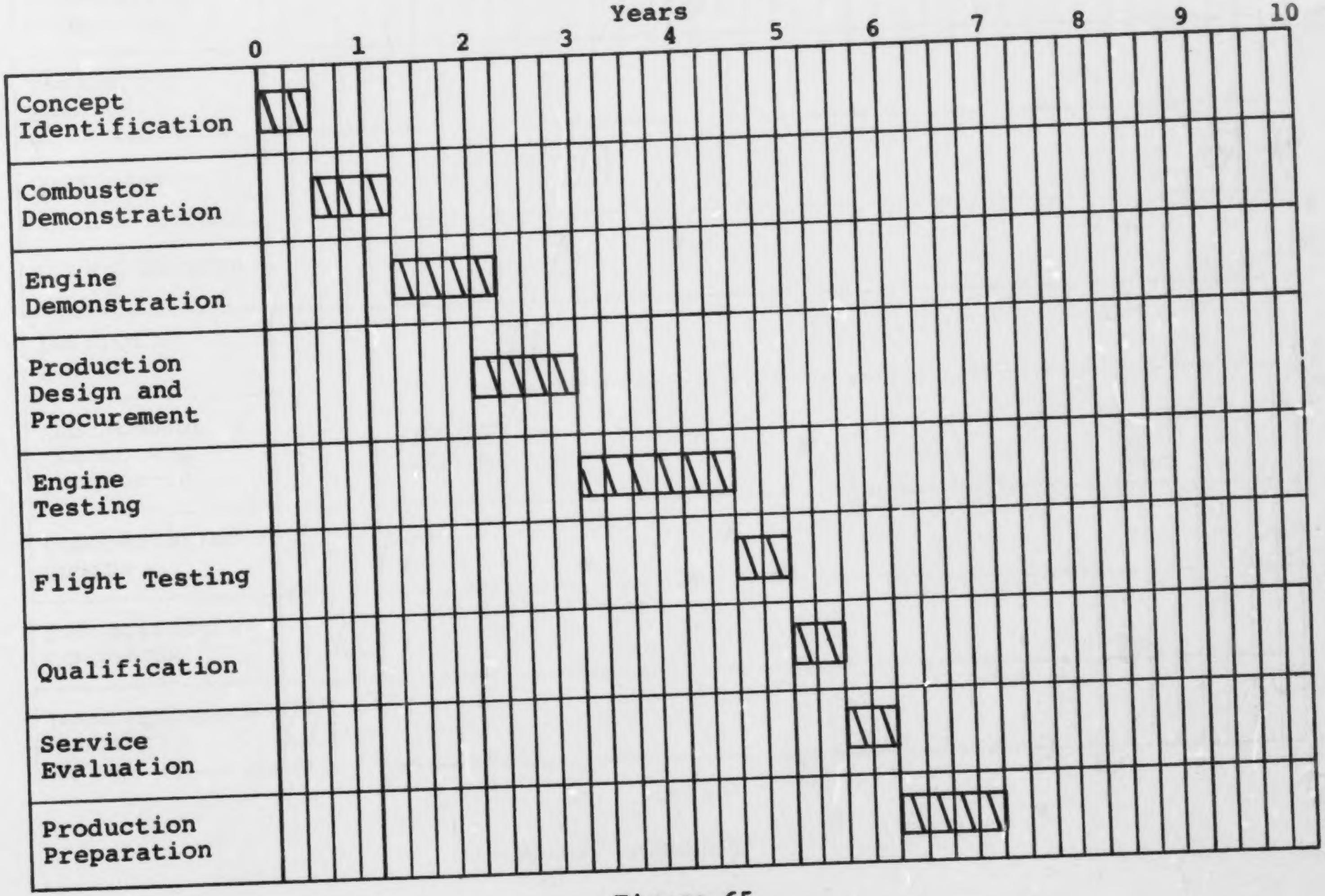


Figure 65

TECHNOLOGY CATEGORY 1
APU
ACCELERATED SCHEDULE

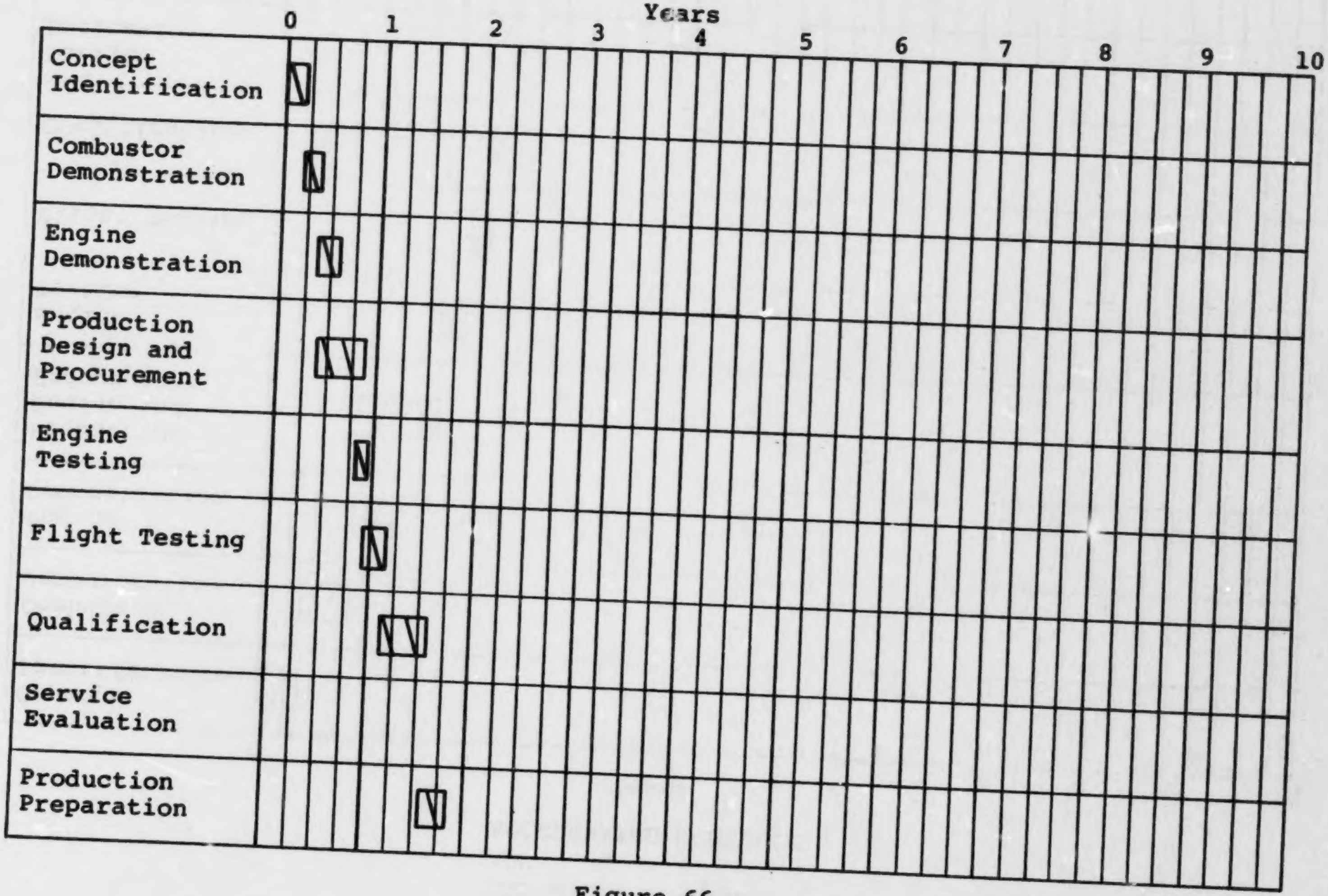


Figure 66

TECHNOLOGY CATEGORY 2
APU
ACCELERATED SCHEDULE

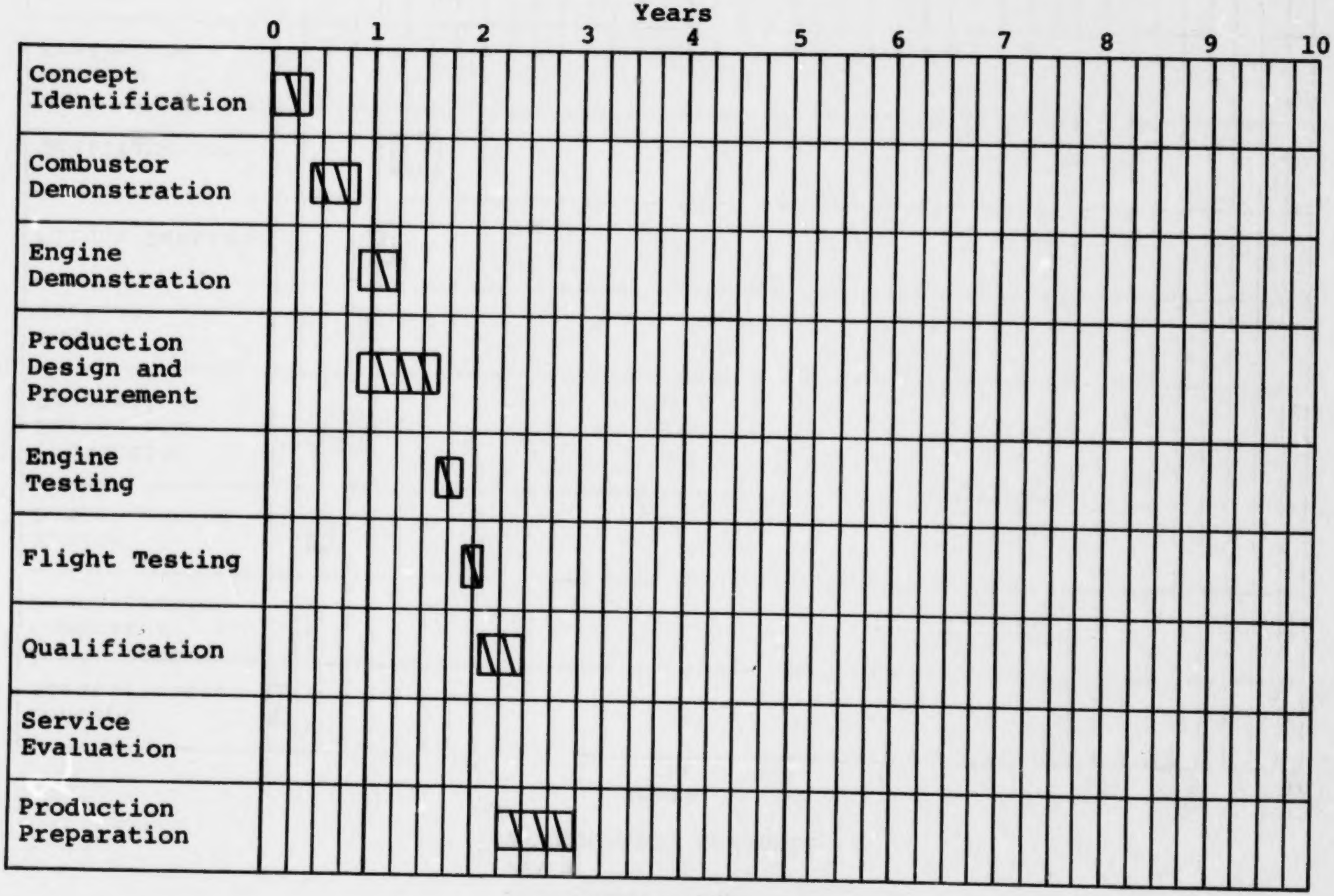


Figure 67

TECHNOLOGY CATEGORY 3
APU
ACCELERATED SCHEDULE

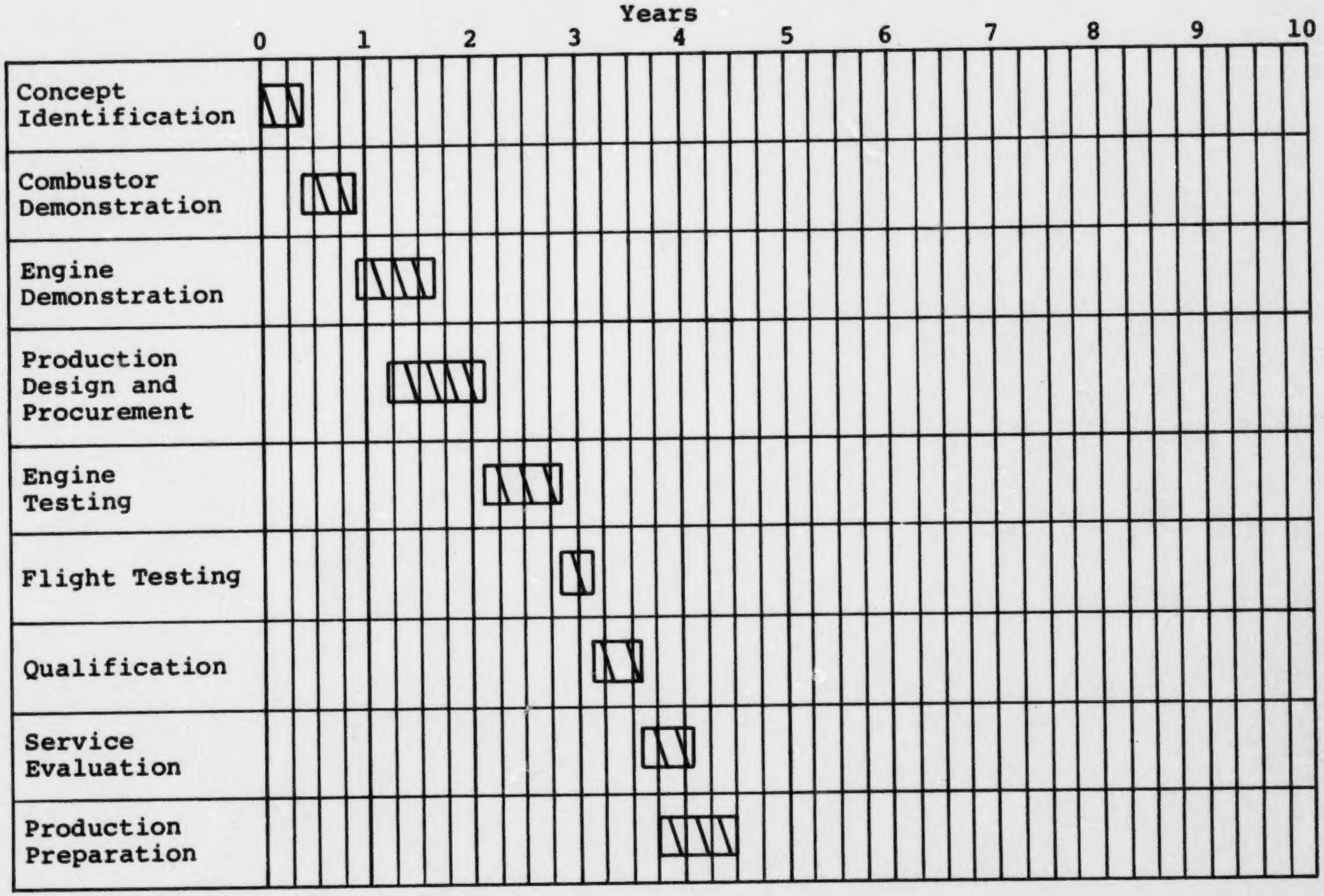


Figure 68

SECTION V: Industry Status

This section presents a summary of the specific control techniques (see Appendix C for descriptions) employed by each manufacturer for each engine in attempting to meet the gaseous emission standards. The information presented indicates the amount of effort put forth by each manufacturer in attempting to comply with the regulations for each engine*, what has been accomplished, the status of each engine, and what can be expected. Also, a brief profile of each engine is included. Since approximately three and a half years have passed since final promulgation of the aircraft emission regulations, an engine's status with respect to the various control concepts under development is presented relative to the lead time schedules developed in Section IV. The dates projected for the implementation of a given control technology concept into newly manufactured engines are based on an accelerated schedule.

It should be noted that for all of the propulsion engines (Class T1, T2, T3, T4, and P2 engines) the control techniques listed for each engine are dry concepts (i.e. do not include water injection for NOx control). Further, the prospects for meeting the 1979 NOx standards, which are given in the profiles, are estimated on the basis of dry technology. Water injection in sufficient quantities could be used to control NOx to the required level on any propulsion engine, if necessary, although care must be taken that not too much water is injected or CO will climb to excessive levels due to the quenching effect of the water. Most manufacturers have demonstrated (development status task no. 3) water injection (category 2 technology) on their respective engines. Hence the estimated implementation dates for incorporating water injection into newly manufactured engines are late 1979 for T1 and P2 class engines (see Fig. 60) and mid 1980 for T2, T3, and T4 class engines (see Fig. 59). This time estimate is considered valid also for engines that currently use water injection for thrust augmentation because in the augmentation application water is used at takeoff only and is delivered at a constant rate. For NOx control water would be injected at takeoff and also at climbout and would be injected at a rate proportional to the fuel flow rate. Hence a water injection control would have to be developed and tested.

A. T1 Class Engines

Class T1 engines are described (FR Vol. 38, N. 136, July 17, 1973, p. 19091) as "...all aircraft turbofan or turbojet engines except engines of Class T5 of rated power less than 8,000 pounds thrust." Generally engines in this class are used on general aviation jet aircraft. The gaseous emissions standards listed below for this class of engines are presently scheduled to go into effect on January 1, 1979.

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*Although it is possible that the manufacturers have expended a greater effort than reported herein, such information has not been made available to the EPA.

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Standard

EPAP
(lbs pollutant per 1000 lbf-hours over the cycle)

HC	CO	NOx
1.6	9.4	3.7

1. AiResearch

a. TFE-731

Profile

Prospects for meeting the 1979 standards:
HC, CO - good with category 1 technology by early 1979
NOx - poor with category 2 technology;
- good with category 3 technology by late 1981
Thrust = 3500 lbs (-2 model)
BPR = 2.66
PR = 13
Combustor type: reverse flow annular
Application: Learjet 35/36 (business jet)
Certification date: August '72
Number delivered: more than 100 for all models combined as of January '75
Production rate: 25 per month for all TFE-731 models combined
Production category after January 1, 1979: III*

Effort Expended

This engine has been selected for testing in the NASA Pollution Reduction Technology Program. Phase I of the anticipated three phases of this program began in November 1974 and was completed in June 1976. According to AiResearch (Ref. 14) Phase I was to cost 693,000 dollars on a cost-share basis, NASA 80% and AiResearch 20% (see Appendix A, Table A-1). During Phase I six versions each of three basic NASA combustor concepts were selected for screening tests. These concepts vary in degree of complexity and thus have varying potential for achieving satisfactory emissions control. The basic concepts selected are listed below along with a brief description of the features of each version.

NASA Concept 1 retrofittable modifications to production combustor (roughly category 1 technology)

Version	Features
Baseline	1. up to 22% bleed at idle 2. air-assist through secondary passage of duplex nozzle at idle

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* This refers to the production categories (expected production situation) defined in part B of Section III.

NASA Concept 1 (continued)

Version	Features
	3. water-methanol injection at takeoff
Mod I	provisions made for sector burning at idle
Mod II	increased swirler airflow
Mod III	piloted airblast fuel nozzles
Mod IV	improved recirculation pattern by making hole pattern changes in the primary zone
Mod V	variable primary-zone equivalence ratio

NASA Concept 2 air assisted/airblast fuel system (roughly category 2 technology)

Version	Features
Baseline	1. 20 (compared to 12 for a production combustor) fuel nozzles 2. nozzles are combination air-assist/airblast type instead of the duplex used in production 3. fuel nozzle swirlers are replaced by grommets at low power to simulate a proposed variable geometry device
Mod I	moved row of primary zone holes upstream on both inner and outer liners
Mod II	added row of primary zone holes to outer combustor liner; increased swirler airflow
Mod III	doubled number of holes added in Mod II and reduced size of each; moved holes upstream for earlier quench; reinstalled baseline swirlers; larger primary zone holes moved downstream to original position
Mod IV	reduced number of outer liner primary zone holes and increased in size; moved them downstream also; primary zone cooling was reduced 33%

NASA Concept 2 (continued)

Version	Features
Mod V	reduced number of outer-liner primary zone holes, increased in size, and moved downstream; reinstalled larger swirlers; restored primary zone cooling air to original amount
Refinement I	unknown
Refinement II	unknown

NASA Concept 3 piloted premixing/prevaporizing fuel system (category 3 technology)

Version	Features
Baseline	1. 20 simplex fuel nozzles in pilot zone 2. forty individual premix/prevaporizing tubes in main zone; these contain simplex nozzles for fuel injection
Mod I	increased pilot zone holes on outer liner from 40 to 120; closed pilot zone cooling holes on outer and inner liner
Mod II	added transpiration cooling holes to inner liner
Mod III	unknown
Mod IV	unknown
Mod V	unknown
Refinement I	unknown
Refinement II	unknown

Phase II (the combustor-engine compatability testing phase) began in June, 1976 and is currently at the design and fabrication task. Candidates for Phase II rig testing are the airblast/air assist system (NASA concept 2), the premix/prevaporization system (NASA concept 3), and a combination of these. This phase of the anticipated three phase project is expected to last 14 months. No dollar estimate of cost is available for Phase II.

Several other category 1 technology concepts were tested "in-house" prior to the start of the NASA work. These were 1) taxi-idle on primary fuel nozzles only, 2) taxi-idle with air assisted primary fuel nozzles (parametric study from 0 to 2.54 lbs/min) and 3) taxi-idle with compressor bleed (parametric study from 0 to 20% compressor airflow). According to the data submitted to the EPA (Ref 14) this "in-house" testing began in 1972. Information quantifying the effort expended for this work has not been submitted to the EPA. However, it should be noted that all of these "in-house" concepts are category 1 concepts which would require the least amount of effort to develop and test.

Results and Status

The most significant results of the TFE-731 tests are summarized in the status table below.

Status (-2 model)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Production (avg. of 6)		6.6	17.5	5.0		
2.54 lbs/min air assist at idle	1	0.5	6.7	5.6	2 (Fig. 58)	early 1979
Piloted airblast* Mod 5	2	0.2	9.2	4.2	2 (Fig. 60)	mid 1980
Premix/prevap.* Mod 3	3-4	0.6	9.2	2.7	2 (Fig. 62)	late 1981

*NASA PRTP results

The data tabulated above indicates that levels of CO and HC below the standards can be achieved with either air-assist or airblast. The air-assist pressure differential (260 psid) required for 2.54 pounds per minute airflow is considered by AiResearch to be higher than can be achieved with a reasonable compressor discharge boost system. An alternate external air-assist system may be required. With both the air-assist and the airblast concepts, NOx remained above the standards. The airblast did reduce NOx by 15 percent; however a 35 percent reduction is required. The premix/prevaporization concept is capable of providing the needed reduction in NOx while controlling HC and CO to a level below the standards.

Projections and Prospects

As noted in the Effort Expended section, the Phase II candidate combustor concepts are the airblast/air-assist system, the premix/prevaporization system, and a combination of these. Both concepts have demonstrated the capability of controlling HC and CO to levels below the standards. So far only the premix/prevaporization combustor has demonstrated the capability to control NOx to a level below the standards. It is expected that development of these concepts will be pursued, especially the premix/prevaporization concept since these concepts offer the best known possibilities for compliance with the standards.

b. ATF3

Profile

Prospects for meeting the 1979 standards:
HC, CO - unknown because of insufficient data to make judgment
NOx - unknown because of insufficient data to make judgment
Thrust = ∿ 5000 lbs
BPR = 3
PR = 22-24
Combustor type: reverse flow annular
Application: potential use for business jets
Certification date: not certified for commercial use
Number delivered: none for commercial use
Production rate: not yet produced for commercial use
Production category after January 1, 1979: IV

Effort Expended

This engine currently has military applications only. However, because of the relatively low rated SFC (0.45 lbm/lbf-hr) this engine has potential application for use on business jets. Probably no effort has been made to reduce the level of gaseous emissions from this engine because of its military application. The only emissions testing that has been done on this engine was conducted to determine the baseline emissions level.

Results and Status

The level of gaseous emissions produced by this engine is summarized in the status table below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.4		Jan. 1, 1979
Baseline		5.8	16.9	4.1		

Projections and Prospects

The potential for reducing HC and CO should be good because of the relatively high pressure ratio of this engine. However, this potential may be limited because of a high surface-to-volume ratio of the reverse flow annular combustor. No estimates of low emissions levels can be made because of insufficient data reported about this engine.

2. Pratt & Whitney Aircraft of Canada

a. JT15D

Profile

Prospects for meeting 1979 standards:
HC, CO - fair with category 2 technology by late 1979
NOx - poor with category 2 technology;
- good with category 3 technology* by late 1981
Thrust = 2500 lbs.
BPR = 3.3
PR = 12
Combustor type: reverse flow annular
Application: Aerospatiale Corvette (business jet)
Certification date: September '73
Number delivered: 50 as of February '75
Production rate: unknown
Production category after January 1, 1979: III

*CO is a problem with category 3 technology

Effort Expended

Low emissions research specifically aimed at reducing JT15D emissions began in 1971 (Ref. 20). For the years 1971 and 1973 a total of 255,000 dollars were spent by PWAC on low emissions research for this engine. No effort was expended in 1972 for JT15D low emissions testing. Information quantifying the effort expended for the years after 1973 is not available for this engine.

Low emissions concepts (reported in Ref. 20 and Ref. 32) that have been tested on this engine are 1) compressor bleed at idle and approach, 2) non-optimized airblast nozzles, 3) rich primary plus delayed quench, and 4) rich primary plus delayed quench plus increased swirl. The extent of testing of these concepts for optimization is not known. The most significant results of this testing are tabulated in the status summary below.

Results and Status

Status (-4 model)

Concept	Technology Category	EPAP			Development Status (Task No.)	Implementation Date
		HC	CO	NOx		
Standard		1.6	9.4	3.7		Jan. 1, 1979
Production (avg. of 6)		12.4	34.6	3.8		
10% bleed at idle & approach	1	5.2	30.0	4.5	5 (Fig. 58)	mid 1978
Rich primary plus increased (37°) air inlet swirl angle	2	0.14	10.9	4.8	3 (Fig. 60)	late 1979

The JT15D has an unusually high idle SFC characteristic for its cycle which adversely affects emissions, especially HC and CO, as the data in the summary above indicates. The modified airflow combustor (rich primary, etc.) has reduced the HC and CO emissions by 99 percent and 68 percent respectively. However, NOx increased 26 percent. To achieve these levels of emissions control the primary zone fuel-air ratio was increased by 20 percent and the intermediate zone fuel-air ratio was decreased 50 percent. This combustor also utilized "delayed quench" which increased the residence times, and swirling air-blast which improved the spray quality. Problems associated with this concept are 4.3% SFC penalty and 6% thrust penalty.

Projections and Prospects

The levels of CO and NOx remain above the standards with either of the reduced emission concepts listed in the status summary. A concept to consider for CO control is the use of bleed at idle and approach along with the airflow redistribution. If the air bleed would be as effective on the modified combustor as it was on the production combustor the first set of values listed in the projected status table below would result. Another concept to consider for CO control is to use air-assist either on the production combustor or in conjunction with the modified combustor. The effectiveness of this concept has already been demonstrated on the TFE-731 engine. Exact levels of emissions cannot be estimated for the JT15D engine since it is not known what if any combustor optimization would be required along with the air-assist.

In order to control NOx it appears that the premix/prevaporization concept being developed by NASA and AiResearch will be required. With this technique it is estimated (see Appendix E) that NOx will be reduced to a EPAP of approximately 3.0. However, the CO EPAP is estimated to be approximately 15.0. The high CO results from the high idle SFC are noted above in Results and Status. Some further CO control concepts would be required. A summary of these projected results is presented below.

Projected Status

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Rich primary plus delayed quench plus increased inlet swirl plus bleed	2	0.1	9.4	5.7	3 (Fig. 60)	late 1979
Premix/prevap.	*3-4	1.0	15.0	3.0	2 (Fig. 62)	late 1981

*NASA technology

The implementation date for the rich primary concept plus bleeds is estimated to be the same as that for the rich primary only concept since the addition of bleeds should not require any extra testing or development. The premix combustor was placed at task 2 (and hence the 1981 implementation date) since Pratt & Whitney Aircraft of Canada has probably investigated both premix and staged concepts. EPA holds this opinion in view of the shared technology between Pratt and Whitney Aircarft of Canada and Pratt and Whitney Aircraft (East Hartford, Conn.) where premix and staged concepts have already been tested for use on the JT9D engines. No data has been reported, however.

3. Lycoming

a. ALF-502D

Profile

Prospects for meeting 1979 standards:
HC, CO - poor with category 1 technology;
- fair with category 2 technology by early 1979;
- good with category 3 technology by late 1981
NOx - good with category 2 technology by early 1978;*
- good with category 3 technology by late 1981
Thrust = 6500 lbs.
BPR = 6.0
PR = 10.7
Combustor type: reverse flow annular
Application: Rockwell Sabreliner (proposed)
Certification date: June 76
Number delivered: none
Production rate: unknown
Production category after January 1, 1979: IV

*HC and CO are above standard with this concept

Effort Expended

Information submitted to the EPA (Ref. 35) indicates that a program to reduce emissions from the ALF-502 engine began in 1973. No information quantifying the amount of manhours and/or money spent in this effort is available. However, it should be noted that all of the ALF-502 low emissions effort has involved category 1 and 2 technology concepts which are the least costly to develop and test.

According to Lycoming (Ref. 35), the initial design of the ALF-502 used dual orifice fuel injectors. Efforts have been made to reduce emissions by incorporating airblast fuel nozzles, and by making changes to the primary zone fuel air ratio, liner wall cooling, primary zone mixing, and primary zone residence time. Lycoming claims (Ref. 35) these tests were designed to encompass the maximum range of airflow distribution possible within this engine and produced such small reductions in emissions that the tests were of little value except to indicate that the EPA 1979 emissions requirements cannot be accomplished through these means. The exact number of configurations tested, and their respective results have not been reported to the EPA (except for the airblast/ combustor modification concept listed in the status table).

Results and Status

The airblast concept noted above was capable of controlling HC and NOx to a level below the standards. However, it is unknown whether or not this configuration represents the optimum airblast-airflow distribution combination. Lower emissions (expecially HC and CO) may be possible with the airblast-airflow redistribution concept. Exact levels cannot be estimated because of insufficient data.

The available results of the the ALF-502 tests are summarized in the table below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Original dual orifice	1	3.3	23.4	3.5	3 (Fig. 58)	late 1978
Original air-blast config.	1	2.3	11.9	4.1	5 (Fig. 58)	mid 1978
Airblast/combustor mod.	2	1.5	11.9	3.0	5 (Fig. 60)	early 1979
Cert. config.* (avg. of 2)	2	2.6	17.8	3.2	7 (Fig. 60)	early 1978

Projections and Prospects

Lycoming anticipates using the technology which has been demonstrated in the NASA ECCP and PRTP programs to assist in the choice of concepts. However, the external air assist (technology category 1) should be considered for reducing emissions, especially HC and CO. As noted in the JT15D section, the effectiveness of air-assist has been demonstrated on the TFE-731 engine. Exact values of emissions cannot be estimated since combustor optimization may be required. It is estimated (similar to method of Appendix E) that the NASA T1 premix/prevaporization concept would control all three gaseous emissions to a level below the standards. The projected levels are presented in the table below.

Projected Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Premix/prevap.**	3-4	0.5	8.9	2.5	2 (Fig. 62)	late 1981

**NASA technology

EPA understands (reference 91) that Lycoming has looked into premix and staged combustors for the ALF-502 engine and it estimated that development has reached the task 2 stage at this point.

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*This configuration was labeled certification configuration by Lycoming but, it is not the configuration that was ultimately certified. Changes in the liner cooling were made because of a durability problem. Emissions data from the certified engine are not available at this time.

4. General Electric

The CF700 and the CJ610 engines have been combined for discussion purposes because of their basic core commonality and their identical combustors. Further, General Electric's efforts to reduce emissions from these engines have also been combined since low emissions concepts should be equally useful on either engine.

a. CF700

Profile

Prospects for meeting 1979 standards:
HC, CO - poor with either category 1 or 2 technology
NOx - already met
Thrust = 4300 lbs.
BPR = 1.6
PR = 6.6
Combustor type: straight flow annular
Application: Dassualt Falcon 20, Rockwell Sabreliner 75A } (business jets)
Certification date: July '64 (-2B model)
Number delivered: 919 thru 1975; 1107 expected thru 1978
Production rate: combined with the CJ610 - 200 per year
Production category after January 1, 1979: I

b. CJ610

Profile

Prospects for meeting 1979 standards:
HC, CO - poor with either category 1 or 2 technology
NOx - already met
Thrust = 2950 lbs.
BPR = 0 (turbojet)
PR = 6.8
Combustor type: straight flow annular
Application: Learjet 24/25 (business jet)
Certification date: Dec. '61 (-1 model)
Number delivered: 1648 thru 1975; 1840 expected thru 1978
Production rate: combined with the CF700 - 200 per year
Production category after January 1, 1979: I

Effort Expended

Efforts to reduce emissions from these two engines began in 1973 according to information available (Ref. 5) to the EPA. According to General Electric (Ref. 5) these efforts have been directed at determining the feasibility and practicality of meeting the emissions standards. Reduced emissions concepts that have been tested for application on both engines are 1) three airflow distribution concepts designed to lean the primary zone 2) three fuel injection concepts to reduce fuel impingement on the combustor walls, and 3) air assisted fuel nozzles. General Electric projected in August 1975 (Ref. 4) that the total cost for a combustor redesign (i.e. airflow redistribution) program through flight testing (line 5 Fig. 59) would be approximately 6.4 million for both engines combined, and that the total cost for a fuel nozzle redesign program (i.e. reduced impingement) through flight testing (line 5 Fig. 58) would be approximately 690,000 dollars for both engines combined. It is not known how much money was actually spent on low emissions testing, however.

General Electric has also tested the effects of three engine operating changes on the CJ610 engine. These changes were increased customer bleed, increased idle thrust, and operating on primary fuel injection alone. No dollar or manhour data is available for this testing. However, it should be noted that these changes are relatively easy to test and therefore the effort required was minimal.

Results and Status

These two engines represent older technology and hence have relatively high SFCs. The HC and CO emissions indices at idle are also very high due to the very rich idle operation of these engines (primary zone equivalence ratio of 1.0 to 1.5). This results in especially high CO emissions. One category 2 concept resulted in reduced CO emissions as a result of a leaner primary zone at idle. However, this was not nearly enough to meet the standards. Some success has been achieved in reducing the HC emission, as a result of the reduced impingement, but still not to a level below the standards. The available data is summarized in the status tables below. Apparently General Electric felt it was not necessary to test NOx control concepts because these engines already meet the NOx standards.

CF700 Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Production		9.1	94	2.2		
Reduced spray cone angle (fuel injector mod)	1	1.6	94	2.2	2 (Fig. 58)	early 1979
air-assisted fuel nozzles	1	11.3	99	No data	2 (Fig. 58)	mid 1979*
addition of venturi design to swirl cup (fuel injector mod)	1	17.9	121	No data	2 (Fig. 58)	early 1979
addition of radial air inflow to swirl cups (fuel injector mod)	1	5.3	97	No data	2 (Fig. 58)	early 1979
addition of inner air scoops (airflow redist.)	2	9.7	78	No data	2 (Fig. 60)	early 1980
addition of radial air inflow to swirl cups plus airflow redistribution	2	---	82	No data	2 (Fig. 60)	early 1980

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*Includes extra six months for service evaluation.

CJ610 Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Production		14.7	155	2.7		
Reduced spray cone angle (fuel injector mod)	1	2.5	155	2.7	2 (Fig. 58)	early 1979
air-assisted fuel nozzles	1	18.2	163	No data	2 (Fig. 58)	mid 1979*
addition of venturi design to swirl cup (fuel injector mod)	1	29.0	200	No data	2 (Fig. 58)	early 1979
addition of radial air inflow to swirl cups (fuel injector mod)	1	8.5	160	No data	2 (Fig. 58)	early 1979
4.2% customer bleed	1	18.8	180	No data	3 (Fig. 58)	late 1978
increased idle thrust	1	13.5	129	No data	3 (Fig. 58)	late 1978
primary injectors only at idle	1	14.7	202	No data	3 (Fig. 58)	late 1978
addition of inner liner air scoops (airflow redisturbution)	2	15.7	129	No data	2 (Fig. 60)	early 1980
addition of radial air inflow to swirl cups plus airflow redist.	2	---	136	No data	2 (Fig. 60)	early 1980

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*Includes extra six months for service evaluation.

Projections and Prospects

The CO emissions can be expected to remain high unless the fuel air ratio can be made lean at idle. It is very difficult to estimate to what level the emissions can be reduced: Any estimate would require very large extrapolations of available data no attempt to do so has been made here.

It should be noted that the implementation dates estimated for the operational changes are based on Figure 58. However, for the increased customer bleeds and the increased idle thrust the remainder of the development tasks (tasks 4 thru 9) could be eliminated. These two operational changes could be used in current production engines without further development or testing.

5. Pratt & Whitney Aircraft

a. JT12A

Profile

Prospects of meeting 1979 standards;
HC, CO - poor with current production combustor
NOx - already met
Thrust = 3300 lbs. (-8 model)
BPR = 0 (turbojet)
PR = 6.7
Combustor type: multiple can
Application: Lockheed Jetstar } (business jets)
Rockwell Sabreliner } (business jets)
Certification: c. 1960
Number delivered: 2900 as of December 1974
Production rate: unknown
Production category after January 1, 1979: I

Effort Expended*

Pratt & Whitney Aircraft reported in Reference 12 that the only emissions work conducted on the JT12 engine consisted of a limited amount of measurements to evaluate the general emissions characteristics. Data reported in Reference 30 indicates that a total of approximately 15,000 dollars was spent for both visible and invisible exhaust emissions work on this engine during the years 1971, 1972 and 1973.

Results and Status

This engine meets the NOx standard with the production combustor due to the relatively low pressure ratio (6.7). The HC and CO emissions are however, very high as a result of the unfavorable operating conditions (low pressure and high fuel flow rate).

Since no low emission combustor concepts have been tested on this engine the only data reported was from the current production model. This data is tabulated in the status table below.

Status (-8 model)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Production		5.2	85	3.2		

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*It should be noted that data reported in Reference 30 indicates that 7,450,000 dollars were spent by Pratt & Whitney Aircraft on basic emissions research and development (i.e., not engine specific) during the time period 1971-1975.

Projections and Prospects

It is doubtful that any reasonable combustor concept would be sufficient to bring this engine into compliance because of the unfavorable operating environment noted above. It is further doubtful that any attempt would be made because of the limited remaining production of this engine.

6. Rolls Royce

The limited submission of emissions and engine performance data by Rolls Royce as of the time of this report did not permit the EPA to make a satisfactory assessment of the status of Rolls Royce. The data tabulated for each engine in the respective status tables represents the only data available for each T1 Class Rolls Royce engine. The reduced emissions technology concepts are unknown but are known to be category 1 or 2 technology. Further, the EPA is not sufficiently familiar with the Rolls Royce test programs to make accurate judgments with respect to combustor development times. Therefore the estimates listed are not as precise as for other engines.

a. M45H

Profile

Prospects for meeting 1979 standards:
HC, CO - good with category 1 or 2 technology by late 1979
NOx - good with category 1 or 2 technology by late 1979
Thrust = 7600 lbs.
BPR = 3.0
PR = 16
Combustor type; straight flow annular
Application: VFW 614
Certification date: August 1974
Number delivered: unknown
Production rate: unknown
Production category after Jan. 1, 1979: III,IV

Effort Expended

Data quantifying the amount of manhours or money spent for reduced emissions development and testing on this engine have not been reported by Rolls Royce. Data from only one low emission concept has been reported for this engine. No technical information about the concept is available. Further it is not known if any other reduced emissions concepts have been tested for use on this engine.

Results and Status

The data reported for this engine using the unknown combustor concept indicates that this engine will be able to meet the level of the standards. It is not known at what task this unknown combustor is in development. It seems probable that this concept is at the engine demonstration task or beyond as some emissions development should have begun prior to selection of the final configuration of this engine. Allowances in the engine should have been made for this combustor so that the hardware changes required to implement it (and hence time) should be a minimum. The status of this engine is tabulated in the table below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Production		6.0	40.7	4.2		
Unknown	1 or 2	0.5	5.3	3.3	3 (Fig. 60)	late 1979*

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* This estimate is based on the assumption that the unknown combustor concept is category 2 technology. Rolls Royce indicated that their reduced emissions combustors would not be available before 1981. Their estimate probably is based upon "normal" time schedule.

Projection and Prospects

Since this engine will be able to comply with the standards with the unknown combustor, probably no further reductions can be expected from it.

b. RB401

Profile

Prospects for meeting 1979 standards:
  HC, CO - good with category 1 or 2 technology by early 1979
    NOx - good with category 1 or 2 technology by early 1979
Thrust = 5400 lbs.
BPR = 4.5
PR = 17
Combustor type: straight flow annular
Application: Business jets
Certification date: estimated to be late 1977
Number delivered: none - deliveries are projected to begin in 1978
Production rate: engine still in development
Production category after January 1, 1979: IV

Effort Expended

This engine is still in development (certification is expected in 1977) so it is expected that low emissions combustor concepts are included in the initial design. Any low emissions development and testing should be part of the normal development and testing of this engine. No data is available which quantifies the amount of manhours or money spent on the development of the combustor. However, the amount of time and money spent should be typical of any new engine combustor development program, and would not necessarily increase because of designing for low emissions.

Results and Status

Only baseline emissions have been reported for this engine. With this baseline configuration HC and NOx standards were achieved, and CO exceeds the standard by about nine percent. The exact EPAP values are tabulated in the status table below.

Status

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		1.6	9.4	3.7		Jan. 1, 1979
Baseline	1 or 2	0.2	10.2	3.6	5 (Fig. 60)	late 1977*

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*Same as the certification date.

Projection and Prospects

According to "Jane's All the World's Aircraft 1975-76" (Ref. 69) this engine was designed to meet the existing emissions standards. If the information supplied to Jane's came from the manufacturer directly, it would suggest that the information supplied to the EPA is incomplete and that lower levels of CO and possibly NOx might be expected.

B. T2 Class Engines

Class T2 engines are defined (FR Vol. 38, N. 136, July 17, 1973, p. 19091) as "...all turbofan or turbojet aircraft engines except engines of Class T3, T4, and T5 of rated power of 8,000 pounds thrust or greater". This class consists of large turbojet and turbofan engines intended for commercial subsonic transports. The gaseous emissions standards, listed below, for this class of engines are presently scheduled to go into effect on January 1, 1979. An NPRM proposing that in-service engines in this class of greater than 29,000 lbs. thrust be retrofit with combustors that control emissions to the standards listed below was issued July 17, 1973. The proposed schedule requires that the retrofit of these engines be completed by January 1, 1983.

Standard

EPAP
(lbs pollutants per 1000 lbf-hours over the cycle)

HC	CO	NOx
0.8	4.3	3.0

1. Pratt & Whitney Aircraft

a. JT9D-7

Profile

Prospects for meeting the 1979 standards:
HC, CO - good with category 2 technology by late 1979
NOx - poor with category 2 technology;
- good with category 3 technology by mid 1981
Thrust = 46,150 lbs.
BPR = 5.15
PR = 22.3
Combustor type: straight flow annular
Application : 747-200
Certification date: June '71
Number delivered: 1400 for all JT9D models combined as of early '75
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

Attachment A of Reference 30 indicates that for the period 1971 through 1975 Pratt & Whitney Aircraft spent approximately three million dollars on development and testing of their own "in-house" low emissions concepts for the JT9D engines (both the JT9D-7 and JT9D-70). The concepts tested for JT9D-7 application (reported in Ref. 12) are compressor bleed and horsepower extraction at idle (category 1), air-assist (category 1), and aerating nozzles (category 2).

The JT9D-7 was also selected for testing in the NASA Experimental Clean Combustor Program (ECCP). This program was conducted in three sequential phases, each individually funded on a cost share basis, with a total of 3.25 million dollars spent (80% NASA and 20% PWA). A description of the efforts, expenditures, and the combustor concepts tested is presented below for each phase.

Phase I: Combustor Screening - Phase I began in December 1972 and was completed in June 1974. Available data indicates that NASA provided a total of 800,000 dollars, while PWA provided the hardware required for testing.

Phase I consisted of rig tests of 32 configurations of three distinct combustor concepts to determine which was the best on the basis of emissions and performance characteristics. The three concepts are described below.

1. Swirl-can Combustor - Each swirl can is made up of three basic components: a carburetor, a swirler, and a flame stabilizer. This combustor is designed such that fuel and air enter the carburetor, mix when passing through the swirler, and then burn in the wake of the flame stabilizer. Thirteen swirl-can combustor configurations involving five major changes were rig tested. These changes were:

1. Changes to the combustor inlet aerodynamics
2. Changes in the carburetor equivalence ratio
3. Changes to flameholding techniques
4. Changes in the fuel injector techniques
5. Addition of liner dilution air

2. Staged Premix Combustor - A description of this type of combustor is given in Appendix C. During Phase I nine configurations that included four design modifications were tested. These modifications involved:

1. diffuser - combustor airflow distribution
2. fuel-air mixture preparation
3. pilot-main burner fuel flow split
4. flame holder design

3. Vorbix - This is also a staged concept designed to provide relatively long resident times at low power operation to minimize CO and HC and also to provide rapid burning and quenching of the reactants at high power to minimize NOx. The pilot burner (used alone at low power) uses conventional type direct fuel injection (i.e., is not premixed). Main burner fuel is injected at higher power conditions and is introduced at the exit of the pilot zone where it is vaporized. Ten configurations incorporating six design variations were tested during Phase I. These variations were:

1. modifications to FINWALL^R (cooling) airflow distribution
2. pilot injector type and airflow schedule
3. main burner fuel source density and fuel spray pentration
4. main burner swirler type and orientation and air schedule
5. main burner fuel injector angle
6. pilot-to-main burner fuel flow split

Phase II: Combustor refinement and optimization: Phase II, which began in July 1974, was completed in February 1976. During this testing a total of 950,000 dollars was spent on a cost share basis, NASA supplying 63% and PWA, 37%.

This phase of the program emphasized refinement and optimization of the best Phase I designs. Two combustor designs were selected for evaluation. These were the vorbix concept and a hybrid concept. A total of 22 configurations, 15 vorbix and seven hybrid, were rig tested during this phase. A description of the combustors is provided below.

1. Vorbix - The Phase II vorbix combustor was based on the Phase I vorbix concept but included the following changes: pilot burner length increased to lower HC and CO (increased residence times); main burner length was shortened, liner height reduced, and the throat height between pilot and main burners was reduced to lower NOx (reduce residence times).

2. Hybrid - This design attempted to combine the best features of two Phase I designs. It incorporated a staged premix pilot burner and a swirl-can mainburner.

Phase III: Combustor-engine testing - Phase III efforts were initiated in July, 1975 and are nearly completed. A total of 1.5 million dollars are being spent (excluding hardware costs) on phase III testing, NASA's share being 1.2 million and PWA's, 300,000; PWA also provided the necessary hardware. In this phase engine tests of the best Phase III combustor were conducted, the best having been determined to be the vorbix concept. Two configurations were tested. Emphasis was put on validating pollution reductions and on determining the acceleration/deceleration characteristics of the combustor.

Results and Status

The most successful concept in terms of reducing HC and CO was the aerating nozzle concept. The HC and CO emissions were reduced by ∿ 95 percent and by 90 percent respectively to levels substantially below the standards. NOx however was reduced only slightly (∿5%) with this concept.

The NASA vorbix and hybrid concepts were successful in simultaneously reducing all three emissions. The vorbix concept was especially effective. During Phase III testing of the vorbix configuration designated S27E, compliance with all three gaseous emissions was demonstrated (Ref. 82). Smoke however was high (SN = 26 compared to standard of 19). This Phase

III testing is particularly noteworthy since this demonstration was with a full scale engine. A summary of these results along with results of the air-assist and aerating nozzle testing is presented in the table below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		5.3	14.3	4.9		
Air-assist	1	1.4	9.4	4.9	3 (Fig. 58)	early 1979**
Aerating nozzle combustor	2	0.2	1.3	4.6	5 (Fig. 59)	late 1979
Vorbix combustor* (S27E)	3	0.3	3.3	2.6	3 (Fig. 61)	mid 1981
Hybrid combustor* (H-6)	3	0.7	3.3	3.5	2 (Fig. 61)	mid 1982

*NASA ECCP Technology
**Includes extra 6 months required for service evaluation

Projections and Prospects

It would seem reasonable to expect Pratt & Whitney Aircraft to continue developing the vorbix concept since it has shown the capability of controlling emissions to a level below the standards.

b. JT9D-70

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with category 1 technology by mid 1979;
  - good with category 2 technology by mid 1980
  NOx - poor with category 2 technology;
  - fair with category 3 technology by mid 1981;
  - good with category 3 technology by mid 1983
Thrust = 51,150 lbs.
BPR = 4.9
PR = 24
Combustor type: straight flow annular
Application: 747-400
Certification date: December '74
Number delivered: 1400 for all JT9D models combined as of early '75
Production category after January 1, 1979: III

Effort Expended

As stated under part a. (JT9D-7), Pratt & Whitney Aircraft has spent approximately three million dollars over a five year period (1971-1975) on their own "in-house" emissions reductions programs for the JT9D-7 and JT9D-70 engines combined. Data reported (Ref. 12 and 28) indicates that the air-assist concept, the aerating nozzle concept, the premix concept, and the vorbix concept have been tested for use on the JT9D-70 engine. This implies that while this engine was not directly involved in the Clean Combustor program it did benefit substantially from this program.

Results and Status

Similar to the JT9D-7 engine, the most successful concept in terms of reducting HC and CO emissions was the aerating nozzle concept. These emissions were reduced ∿ 85 percent and ∿ 60 percent respectively. The resultant levels of these emissions were substantially below the standards. NOx was reduced approximately 15 percent.

The two staging techniques each reduced NOx by approximately 35 percent relative to the production combustor. However, a 50 percent reducton is required.

Reported results are tabulated in the status summary below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		1.2	5.9	5.8		
Air-assist	1	0.3	3.9	5.8	2 (Fig. 58)	mid 1979**
Aerating nozzle combustor	2	0.2	2.3	4.8	3 (Fig. 59)	mid 1980
Premix combustor	3	0.7	3.5	3.8	2 (Fig. 61)	mid 1982*
Vorbix combustor	3	1.0	6.0	3.9	2 (Fig. 61)	mid 1982*

Projections and Prospects

Two other staged combustors should be considered for use in this engine. These are the ECCP vorbix concept S27E which was demonstrated in the JT9D-7 engine, and the General Electric double annular concept. EPA estimates that these would reduce NOx by ∿ 40 percent and

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*NASA has predicted that premix combustors will not be available until 1985. The NASA time schedule is considered "normal".

**Includes extra six months for service evaluation.

~ 47 percent respectively while controlling HC and CO to a level below the standards. (Estimates were made in accordance with Appendix E and Ref. 59). The vorbix would probably be available approximately two years sooner because of Pratt & Whitney's extensive experience in developing this concept. Presumably no development of the double annular concept has been initiated by PWA. A summary of these projections is presented below.

Projected Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Double annular*	3	0.3	3.2	3.1	1 (Fig. 61)	mid 1983
Vorbix* S27E	3	0.3	3.2	3.5	2 (Fig. 61)	mid 1982

*NASA technology

c. JT10D

Profile

Prospects for meeting 1979 standards:
HC, CO - good
NOx - good
Thrust = 23,000 lbs.
BPR = 5.35
PR = 28
Combustor type: straight flow annular
Application: proposed for 707, DC-8, DC-9, 7X7
Certification date: projected for 1979
Number delivered: none - engine still in development
Production rate: none - engine still in development
Production category after January 1, 1979: IV

Effort Expended

Data submitted to the EPA (Ref. 30) indicates that approximately 583,000 dollars was spent on low emissions efforts for the JT10D engine during the years 1973-1975. The JT10D is in the pre-development demonstrator phase, and the expenditure noted above is that portion of the total combustor development cost estimated by Pratt & Whitney Aircraft (Ref. 87) to be attributed to low emissions efforts.

Results and Status

No emissions data has been reported for this engine.

Projections and Prospects

The JT10D is a newly designed engine (first tested in August 1974) based on JT9D technology. It is being developed for minimum fuel consumption and low emissions and should be expected to comply with the standards since much of the design work was done after the standards were promulgated.

2. General Electric

a. CF6-50C

Profile

Prospects for meeting the 1979 standards:
  HC, CO - fair with category 1 technology before 1979
    NOx - poor with any known control (category 1-3)
Thrust = 49,900 lbs.
BPR = 4.4
PR = 29.5
Combustor type: straight flow annular
Application: DC-10 Series 30, A300-B
Certification date: c. 1972
Number delivered: more than 400 as of January 75
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

The bulk of GE's work on this engine since January, 1973 has been in support of their contractual effort (cost-sharing) with NASA's Experimental Clean Combustor Program (ECCP). This major program, involving approximately 3.5 million dollars,(∿ 80% NASA and ∿ 20% GE plus GE supplying the necessary hardware required for testing), is divided into three phases, the first being a preliminary screening phase of a number of potential concepts, the second being a development phase wherein the best two concepts were further refined, and the third being an engine demonstration phase of the best concept. As the program goal was the development of technology with the capacity to meet the 1979 EPA standards, it was recognized early that only category 3 concepts would be acceptable. Hence, the major portion of the effort was directed at such technology.

The screening phase (Phase I) included rig investigation of the following concepts (reference 1):

(1) Swirl can modular dome

This is essentially a mix of control approaches, all wrapped up into a single, but extensive nozzle modification: premix (modest degree), airblast, and lean primary. Seventeen versions were investigated in a parametric study. (category 2).

(2) Lean dome single annular combustor

This is basically a conventional combustor with the airflow redistributed to provide a very lean primary zone equivalence ratio. The additional air was admitted through the new carbureting swirl can nozzles, holes in the dome, and restrictions in the dilution parts of the liner downstream, as necessary. Four configurations, with and without simulated bleed at idle, were examined. (category 2-3).

(3) Double annular combustor -

This concept marks a major departure from conventional combustor design as fuel staging is involved. As the name suggests, there are, in effect, two combustors within one, one designed for high power, but low NOx, operation (lean primary), and the other for near stoichiometric operation at low power to consume HC and CO better. Six versions were examined. (category 3).

(4) Radial/Axial combustor -

This is basically just another version of the fuel staging concept. Seven configurations were investigated. (category 3).

In the development phase (Phase II) of the contract (reference 75), the two fuel staging concepts (double annular and radial/axial) were perfected further and subjected to various performance tests (non-emissions) such as altitude relight, carbon deposition, etc. A total of 66 rig (full and sector) tests were performed through this phase to investigate the emissions improvements and performance of different modifications.

In the engine testing phase (Phase III) now underway, one concept (the best version of the double annular) is being tested in an engine for emissions and other engine related performance criteria (acceleration, etc.).

Prior to 1973 most of the General Electric effort evidently was directed towards establishment of baseline emissions and understanding of the basic physical and chemical phenomena. Additional in-house work (for which cost information is not available) has been done up to the present in an effort to establish simpler alternatives to the approaches pursued in the NASA program (references 8 and 73). NOx control was explored by techniques of quick quenching, and lean primary, all category 2 concepts. HC and CO control was explored by bleed and sector burning at idle, both category 1 concepts. The amount of effort in exploring these category 1 concepts is small in view of their simplicity. Testing normally involves a parametric investigation of the control. In these category 1 cases, these were amount of bleed and the size and location of the sectors. Some additional support testing is necessary in some instances, in particular with water injection and sector burning, to investigate potential durability problems. To EPA's knowledge, GE has not continued with these studies.

GE is also involved in other government sponsored programs (see Appendix A) at present directed towards high altitude cruise emissions (NOx) and very low HC, and CO emissions (i.e., directed at the 1981 standards).

Results and Status

The most significant results of the above testing are tabulated below.

Status

			EPAP			
Concept	Technology Category	HC	CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		4.3	10.8	7.7		
Production combustor plus sector burn at idle	1	0.3	5.3	7.8	3 (Fig. 58)	late 1978
Single annular lean dome	2-3(est)	10.4	12.7	7.2	2 (Fig. 61)	***
Double annular*	3	0.3	3.0	4.3	3 (Fig. 61)	mid 1981**
Radial/axial*	3	0.9	9.6	4.3	2 (Fig. 61)	mid 1982**

*ECCP Technology

**NASA predicts it may take until 1985 to implement staged combustor techniques. The NASA time schedule is considered "normal".

***Not likely to comply under any circumstance.

Projection and Prospects

The data above indicate that the sector burn concept is successful in reducing HC and CO emissions substantially but only HC is reduced to a level below the standards. This is due in part to the low idle power (3.4% of rated power) of this engine and in part to the short combustor (short residence time). If the engine idle speed were increased to say 6% of rated power, the CO emissions should be reduced to an EPAP value of approximately 3.4 and HC emissions would be reduced to an EPAP value of approximately 0.2. The effect on NOX should be negligible. Alternatively, increased bleed at idle would provide the same effect without suffering the adverse consequences of a higher thrust level. Both solutions result in a fuel consumption penalty, however, at idle.

The single annular lean dome combustor is a considerable failure and emphasizes the problems to be encountered when the single primary zoned combustor (i.e., conventional) is pushed beyond its technology capabilities. Although further development would probably yield some improvement, it is apparently futile to attempt to reduce all three pollutants simultaneously with such a configuration.

The double annular concept produces emissions of HC and CO below the standards. NOx is reduced by 45 percent but is still above the standards. A problem with respect to NOx emissions from the double annular combustor is that it has a higher flame temperature than the baseline combustor at approach. This is a result of a high fuel air ratio for pilot-only operation during this mode. In spite of this, the NOx level shown for the double annular concept is judged by NASA to be nearly optimum for the level of technology evaluated. The radial/axial concept is also capable of simultaneously reducing all three emissions, but none are reduced to the levels required by the standards. According to NASA both the double annular and the radial/axial concepts represent major steps for reducing engine emissions without compromising performance.

Either staging concept is faced with certain, as yet unreasolved, development difficulties, most notably that of the fuel control. Approach power requires pilot-only operation in order to retain low CO characteristics. However, the fuel flow rate at cruise (high altitude) is comparable to that at approach; yet, there, the fuel must be distributed between the two stages and, in fact, more must be supplied to the secondary than to the pilot. A control system then must be able to distinguish between these two flight regimes despite the similar total fuel flows. Either altitude or speed sensing must be linked into the fuel control. Another problem is that of the transition between pilot-only (up to approach) and staged (beyond approach) fuel flows. The transition must occur without thrust perturbations or flame blowout.

b. CF6-6

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with cateogry 1 technology by early 1979
    NOx - poor with any known control (category 1-3)
Thrust = 38,900 lbs.
BPR = 5.9
PR = 24.7
Combustor type: straight flow annular
Application: DC-10 Series 10
Certification date: September '70
Number delivered: as of January '75 more than 350
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

Little actual work on this engine has been expended to EPA's knowledge (references 6, 7, 8, and 47). Although this engine uses a different combustor from that in the CF6-50 and the operating conditions are also different, there is sufficient similarity that the results of concept selection in the CF6-50 program can be expected to be applicable here also. This is an acceptable and economic approach in this instance. Consequently, the only testing done on this engine to date has been to explore baseline emissions and the potential of compressor bleed (category 1 technology).

At this point in time, however, it is suprising that the successful technology concepts identified in the CF6-50 work have not been introduced into the CF6-6 program. Specifically, engine data for modest technology (category 1 or 2) application (e.g., sector burning, combined if necessary, with compressor bleed or increased throttle) might have been available by now. Also, in view of the initial successes of the double annular combustor in the CF6-50 (reference 75) and in view of the long development leadtimes, one might have expected to see the initial steps taken by this time to incorporate this combustor into the -6.

Results and Status

The limited actual engine data available are presented below:

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		3.4	10.0	7.2		
Compressor bleed	1	1.7	8.0	7.4	4 (Fig. 58)	mid 1978

Projections and Prospects

The low emissions concepts being evaluated for the CF6-50C engine are considered to be applicable to the CF6-6D engine and the results are expected to be similar in terms of emissions reductions. Assuming this, the following table represents what is potentially available.

Projected Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production combustor plus sector burn at idle	1	0.2	4.9	7.3	2 (Fig. 58)	early 1979
Production combustor with sector burning and compressor bleed at idle	1	0.1	3.9	6.7	2 (Fig. 58)	early 1979
Double annular	3	0.2	2.8	4.0	2 (Fig. 61)	mid 1982

Instead of combining the two category 1 concepts, sector burning and compressor bleed, to achieve sufficiently low HC and CO levels, it is possible also to simply increase the engine power level at idle instead of bleeding the compressor although this would be less desirable because of the added thrust. Either way there is a fuel penalty at idle.

Note that the double annular combustor is not expected to meet the NOx standard although it does very well. The present development difficulties attendant with this combustor are described in the Projections and Prospects Section of the CF6-50 discussion.

c. CFM56

Profile

Prospects for meeting the 1979 standards:
HC, CO - fair with category 2 technology by early 1979
- good with category 3 technology by mid 1982
NOx - good with category 3 technology by mid 1982
Thrust = 22,000 lbs.
BPR = 6.0
PR = 25
Combustor type: straight flow annular
Application: proposed for BAC-111, DC-9, 727, A300, 707, DC-8
Certification date: expected late '77 or early '78
Number delivered: none - not yet in production
Production rate: none - not yet in production
Production category after January 1, 1979: IV

Effort Expended

This engine is in a little different situation than the other GE T2 class engines in that it is not yet certified. This means that the present combustor is not so inextricably bound to the engine that change is difficult. Furhermore, as the engine has no in-service history behind it, the stringent durability requirements of an older engine are not present. Emissions performance data is scant for this engine (references 8, 38, 39, 47, 73, and 76), for just as the effort on the CF6-6 has been small, pending the outcome of the various CF6-50 studies, so has the effort here. Nevertheless, sector burning has been investigated in both the baseline combustor (category 1) and a modified combustor (category 2). The actual extent of this testing (i.e., the degree of optimization), however, is unknown to the EPA at this time.

Results and Status

The limited actual engine data are presented below:

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
PFRT (Baseline)		1.7	12.8	4.7		
Baseline combustor plus sector burn at idle	1	0.9	10.9	4.8	4 (Fig. 58)	mid 1978
Modified PV combustor plus sector burn at idle	2	0.2	9.7	4.8	4 (Fig. 59)	early 1979*

*Service evaluation excluded, replaced by entry into service experience.

Projections and Prospects

This engine produced more CO than is expected from a modern high bypass ratio engine. This is due to its relatively short combustor and subsequently short residence time. Efforts to improve combustion efficiency have resulted in reducing only HC to a level below the standards. The level of CO listed is based on data submitted to the EPA by General Electric (Ref. 39). However, at the EPA Hearing on Aircraft held January 27-28, 1976, General Electric recommended that the CO level for newly manufactured T2 class engines should be set at an EPAP of 5.1 (Ref. 47

and 48). On the other hand, according to the 1975-1976 "Jane's All The World's Aircraft" (Ref. 69), this engine was designed to meet the 1979 gaseous emissions standards. Assuming that Jane's obtained its information accurately from the manufacturer, it can be surmised that further CO and NOx improvement can be expected from this engine, and that the CO emissions indicated for this engine do not represent optimal technology.

Additional improvement in the CO emissions can most likely be obtained by modest means through the use of compressor bleed in addition to sector burning although with the combustors now available (baseline or modified PV) the CO standard would most likely still not be met.

Use of the double annular combustor (technology category 3) in this engine would probably control all three gaseous emissions to levels below the standard as is indicated in the table below. The fact that an improvement is projected for CO emissions through the application of a category 3 concept (combined with the best compatible category 2 concepts in the pilot chamber to control HC and CO) suggests that the two combustors on which the sector burning was tried have not been fully optimized and further CO improvements can be expected with category 2 technology. This is probably recognized by GE and is the basis for their CO standard recommendation referred to above. The projected status of the CFM56 engine is summarized in the table presented below.

Projected Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Modified PV combustor plus sector burn and compressor bleed	2	0.1	7.8	4.8	3 (Fig. 59)	mid 1980
Double annular*	3	0.4	3.9	2.7	2 (Fig. 61)	mid 1982

*ECCP technology

3. Rolls Royce

As with the T1 engines the limited submission of emissions and engine performance data by Rolls Royce as of the time of this report did not permit the EPA to make a satisfactory assessment of the status of Rolls Royce. The data tabulated for each engine in the respective status tables represents the only data available for each Rolls Royce engine. The reduced emissions technology concepts are unknown in specifics but are either category 1 or 2 technology. Further, the EPA is not sufficiently familiar with the Rolls Royce test programs to make accurate judgments with respect to combustor development times. Therefore the estimates listed are not as precise as for other engines.

a. RB211

The discussion of the emissions programs of the RB211-22B and the RB211-524 has been combined because of basic design similarities and hence emissions characteristics. Furthermore, the lack of detailed information precludes any meaningful discussion at a level which would distinguish between the two.

Profile RB211-22B

Prospects for meeting the 1979 standards:
HC, CO - fair with category 1-2 technology (by early 1980)
NOx - poor with category 1-2 technology;
- good with cateogry 3 technology (status unknown)
Thrust = 42,000 lbs.
BRP = 5.0
PR = 25
Combustor type: straight flow annular
Application: L-1011-1
Certification date: April '73
Number delivered: 450 including modified RB211-22C engines as of April '75
Production rate: unknown
Production category after January 1, 1979: III

Profile - RB211-524

Prospects for meeting the 1979 standards:
HC, CO - good with category 1-2 technology (by early 1980)
NOx - poor with category 1-2 technology;
- good with category 3 technology by (status unknown)
Thrust = 50,000 lbs.
BPR = 5.0
PR = 25
Combustor type: straight flow annular
Application: proposed for B747, A300B
Certification date: c. 1975
Number delivered: unknown
Production rate: unknown
Production category after 1, 1979: III

Effort Expended

Data submitted by Rolls Royce (Ref. 44 and Ref. 45) indicates that programs to reduce emissions began in 1973 after the publication of the original NPRM in December 1972. Details about the RB211-22B program were not available to EPA at the time of this report.

Based on the limited submittals, it is known that rig testing of several basic reduced emissions concepts has been conducted in order to determine their usefulness on RB211 engines. The concepts tested are (from Ref. 81) 1) fuel preparation and injector modifications (category 1), 2) compressor bleeds (category 1), 3) sector burning (category 1), 4) operating speed (category 1), 5) staging (category 3), and 6) premix with staging (category 3). It is not known how many versions of each were tested and whether or not any parametric studies were made. Results from this low emissions testing have not been reported, and thus the effectiveness of each in reducing emissions cannot be evaluated.

The only level-of-effort information (from Ref. 45) indicates that during 1975, 63 percent of the RB211 combustor rig development funding was allocated to the development of pollution control combustors. No information quantifying the total dollars or manhours used for emissions reduction programs in 1975 or any other year is available.

Results and Status

These engines produce much higher HC and CO emissions than is expected from a modern low SFC T2 class engine. The only low emission data available, tabulated in the status table below, indicates that all emissions were reduced including NOx surprisingly; only HC was reduced to a level below the standards in the -22B, while for the -524, both HC and CO were reduced to levels below the standards due mostly to the more favorable operating pressure at idle in that model than in the -22B.

Status (RB211-22B)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		14.0	20.0	7.3		
Unknown	1 or 2	0.7	5.6	6.8	4 (Fig. 59)	early 1980

Status (RB211-524)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		8.3	11.9	8.9		
Unknown	1 or 2	0.5	3.7	7.1	4 (Fig. 59)	early 1980

Projections and Prospects

Insufficient data prevents any useful projections from being made. However, because of the design and operational similarities between this engine and the JT9D or CF6 engines, any of the low emissions combustor techniques discussed previously for the JT9D or CF6 should be applicable to this engine, especially the aerating nozzle concept, the double annular concept and the vorbix concept. Therefore, it is expected that the emissions levels would be comparable to those of the JT9D engine with an optimized combustor.

b. Spey

The discussion of the emissions programs and performance of the Spey 511 and the Spey 555 has been combined because of basic design similarities and hence emissions characteristics.

Profile - Spey 511

Prospects for meeting the 1979 standards:
  HC, CO - poor with any technology
    NOx - poor with category 1 or 2 technology;
      - unknown with category 3 technology
Thrust = 11,400 lbs.
BPR = 0.64
PR = 18.9
Combustor type: multiple cans
Application: Grumman Gulfstream II
Certification date: c. 1962
Number delivered: unknown
Production rate: 50 per year for all Spey models
Production category after January 1, 1979: II, III

Profile - Spey 555

Prospects for meeting the 1979 standards:
HC, CO - poor with any technology
NOx - poor with category 1 or 2 technology
- unknown with category 3 technology
Thrust = 9850 lbs.
BPR = 1.0
PR = 15
Combustor type: multiple cans
Application: F-28
Certification date: c. 1962
Number delivered: unknown
Production rate: 50 per year for all Spey models
Production category after January 1, 1979: II, III

Effort Expended

Except for the EPAP data presented below, little is known of the extent of the program for improving the Spey's emissions. Neither the specifics of the concepts tested nor the extent of testing are known to the EPA for this family. The manufacturer has claimed to have implemented an "intensive programme" (reference 44) and certainly sizeable reductions in HC and CO emissions have been realized, yet because of the basic combustor design of the production engine and the relatively high SFC (reflecting its age-certification around 1962), the family is a long way from compliance with even the HC and CO standards. In summary, little was known at the time of this report as to the extent of the program for improving the Spey's emissions.

Nonetheless, the following remarks can be made. First, Rolls Royce has evidently concluded on the basis of its own analysis that the engine cannot meet the standards with any technological effort whose development cost would be recoverable within the estimated remaining production of the engine. Uneconomical technology includes, apparently, any category 3 concepts and any further category 2 effort. The concepts which have been tried are (reference 81):

(1) engine speed (category 1)
(2) combustor airflow redesign (category 2)

The engine speed control has been engine tested, the other concept, only rig tested. The extent of these investigations and the degree of refinement pursued is unknown. In addition, Rolls Royce evidently planned to examine in 1975 (reference 81) certain advanced concepts (variable geometry and staged combustion). However, no results have been made available to the EPA.

On the other hand, in response to EPA's inquiry at the January, 1976 hearing, Rolls Royce reported (reference 45) that 78% of the total combustor rig development funding for the Spey was allocated for pollution control. The true extent of the commitment represented by this expenditure, however, cannot be appreciated without knowledge of the actual monies spent. In view of the maturity of the engine and the already established excellent durability record of the Spey combustor, it is understandable that most of the combustor development still going on is related to emissions improvements.

Results and Status

The only results known to the EPA regarding the Spey family are:

Status - Spey 511

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		35.7	35.7	7.8		
Unknown	1 or 2	5.0	20.7	7.4	unknown	unknown

Status - Spey 555

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production		46.2	63.2	4.3		
Unknown	1 or 2	6.0	23.4	4.2	unknown	unknown

No estimates of the implementation dates are possible by using the leadtime analysis in section IV as no knowledge of the development status of the control concepts is known. The manufacturer has recommended exemption for the Spey family, so no recommended time applicable for this family is available.

Projections and Prospects

It is difficult to discuss alternatives in view of the lack of knowledge of what has been attempted and its level of success. The following general statements are pertinent, however. The Spey engine family is very similar in function, design, and performance to the JT8D family of Pratt and Whitney (compare profiles) except that the Speys are smaller (50 to 80% the thrust levels of the JT8Ds). Both families have comparable bypass ratios, pressure ratios, turbine inlet temperatures, and burner design, all of which reflect the fact that both engines are of the same generation (early 1960s). The air loading of the Spey is slightly higher (worse) than that of the JT8D (air loading parameter of 0.68 vs. 0.53 for two representative models), but not enough to explain the relative success of the JT8D over the Spey. Surface-to-volume effects in the combustors cannot be evaluated as that information is not available for the Spey.

The prospects for this engine do not appear encouraging on the basis of what is known, but then again, the causes of the discouraging data cannot be appreciated. Because of its similarity with the JT8D, the emissions performance of the Spey should be comparable with the JT8D, but this has not been realized.

C. Class T3 engine

Class T3 engines means all aircraft gas turbine engines of the JT3D model family. This special class was created in order to implement the special smoke retrofit standard for these engines. The gaseous emissions standards and compliance date are however, the same as those for the T2 class engines. The standard is listed below for convenience.

Standard

EPAP
(lbs pollutant per 1000 lbf-hours over the cycle)

HC	CO	NOx
0.8	4.3	3.0

1. Pratt & Whitney Aircraft

a. JT3D

Profile

Prospect for meeting the 1979 standards:
HC, CO - poor
NOx - poor
Thrust = 19000 lbs. (-7 model)
BPR = 1.4
PR = 13.5
Combustor type: multiple cans
Application: 707 - 320c, DC-8
Certification date: c. 1960
Number delivered: 8300 for all models combined as of the end of 1974
Production rate: unknown
Production category after January 1, 1979: I

Effort Expended

Reported data (Ref. 30) indicates that approximately 2.2 million dollars have been spent on emissions reductions on the JT3D/TF33* engines. Efforts to develop a low emission combustor have been mainly devoted to reducing smoke with an aerating nozzle combustor. There has apparently been no attempt to comply with the gaseous emission standards.

Results and Status

By utlizing the aerating nozzle concept some reduction in HC and CO has been made at the expense of NOx. The emissions data from this reduced smoke combustor are presented below along with the emissions data from the production combustor.

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*The TF33 is a military engine. Presumably some of the low smoke effort has been financed by the Air Force. It is not known how much, however.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1979
Production (-1 model)		34.2	40.8	3.8		
Aerating nozzle combustor (-7 model)	2	18.0	26.2	5.6	8 (Fig. 59)	early 1978

Projections and Prospects

It is doubtful that further developments leading to lower emissions will be made because the aerating nozzle combustor is already being used in the smoke retrofit program, and also because this engine is nearing the end of its production. Development of still another low emissions combustor would probably not be economically justified because of limited number of engines expected to be produced after January 1, 1979.

D. Class T4 Engine

Class T4 engines means all aircraft gas turbine engines of the JT8D model family. As with the T3 Class, this class was created for the implementation of a special smoke retrofit standard and it must also comply to the T2 Class emissions standards and implementation date. The gaseous emissions standard is tabulated below for convenience.

Standard

EPAP
(lbs pollutant per 1000 lbf-hours over the cycle)

HC	CO	NOx
0.8	4.3	3.0

1. Pratt & Whitney Aircraft

a. JT8D

Profile

Prospects for meeting the 1979 standards:
  HC, CO - fair with category 2 technology by mid 1979
    NOx - poor with category 2 or 3 technology
Thrust = 16,000 lbs. (-17 model)
BPR = 0.99
PR = 16.9
Combustor type: multiple cans
Application: 727, 737, DC-9
Certification date: c. 1962
Number delivered: 7200 for all models combined as of the end of 1974
Production rate: unknown
Production category after January 1, 1979: II, III

Effort Expended

The JT8D engine was selected as one of the base engines in the NASA Pollution Reduction Technology Program (PRTP). The JT8D program was initiated in August 1974, with Phase I of an anticipated three phases which ended in December 1975. During this program a total of 846,000 dollars (Ref. 87) was spent on a cost share basis, 37% PWA funds and 63% NASA funds. This program was divided into three basic elements, each investigating successively more complex combustor concepts. Element I consisted of investigating modifications to the existing JT8D combustion system (basically category 1 and 2 concepts). These were: airblast fuel nozzles, airflow distribution, and fuel-air carburetion. A total of six configurations were tested. Element II consisted of testing nine configurations of the vorbix combustor (category 3 technology). This concept has more potential for meeting the standards than Element I concepts, but it is more complex and would be more difficult to adapt to an operational engine. Element III consisted of testing five configuraitons of the premix/prevaporization combustor concept (category 3-4 technology). This concept represented the greatest difficulty of those considered in this program for adapting to operational engines. However, it also has the highest potential for meeting the standards.

Available data from Reference 30 indicates that Pratt & Whitney Aircraft also spent an additional 1.1 million dollars on JT8D reduced smoke and gaseous emissions efforts during the time period 1971-1975. Most of this effort seems to have been devoted to testing of the aerating nozzle concept. Some additional testing has also been done with the external air-assist concept.

Results and Status

Use of the aerating nozzle combustor concept resulted in an 80 percent reduction in HC, a 70 percent reduction in CO, and a 15 percent reduction in NOx. However, only HC was reduced enough to meet the standards. Reductions to the levels indicated are significant because this engine represents older technology and hence has a relatively high SFC. However, the JT8D-17 aerating nozzle HC and CO emissions indices reported are among the lowest from any combustor of technology rating 2 complexity. Further major EI reductions would not be expected in the near future.

The aerating nozzle technique, however, does not adequately control NOx. Some type of staged combustor such as the vorbix or a premix/prevaporization combustor would be required. The vorbix concept that was judged best by NASA (Ref. 34) reduced NOx by 48 percent. This percentage reduction in NOx was the best of any of the combustors tested in the ECCP or PRTP (NASA programs.) NOx reductions to lower levels would therefore seem unlikely in the near future. Additional development is still needed to achieve acceptable exit temperature pattern factors. Further, this concept has an altitude relight deficiency which would also need to be resolved possibly at the expense of the emissions control. Available test results are summarized in the status table below.

Status (-17 model)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.8	4.3	3.0		Jan. 1, 1978
Production		3.1	12.8	6.8		
Air-assist	1	1.2	10.5	7.1	3 (Fig. 58)	early 1979**
Aerating nozzles	2	0.8	5.0	7.1	5 (Fig. 59)	mid 1979
Airflow redistribution*	2	1.5	6.8	7.4	2 (Fig. 59)	early 1981
Vorbix*	3	0.2	9.0	4.3	2 (Fig. 61)	mid 1982
Premix/ prevaporized*	3-4	0.4	14.3	4.6	2 (Fig. 61)	mid 1982

*NASA technology
**Includes extra 6 months for service evaluation

Projections and Prospects

As noted above the JT8D represents an older technology low bypass ratio engine and hence has a relatively high SFC. The aerating nozzle concept in this engine produces among the lowest levels of HC and CO emissions indices, but only marginally meets the HC standard. Therefore reductions to levels below those of the aerating nozzle levels listed in the table above are not likely in the near future. Further, NOx reductions greater than the 48 percent reduction noted above (achieved as a result of using the vorbix combustor) are also unlikely in the near future. These two concepts are not mutually exclusive and could be used together in a single combustor to control all three emissions. However, it is doubtful that HC and CO would be as low as those for the aerating nozzle concept listed, or that NOx would be as low as that for the vorbix combustor listed. The exact level of emissions for such a combustor cannot be predicted.

E. P2 Class Engines

The P2 Class covers all aircraft turboprop engines (see FR Vol. 38, N. 136, July 17, 1973, p. 19091). These engines are used on medium to heavy general aviation aircraft with some used on commercial air transports. The gaseous emissions listed below for these engines are presently scheduled to go into effect on January 1, 1979.

Standard

EPAP
(lbs pollutant per 1000 horsepower-hours over the cycle)

HC	CO	NOx
4.9	26.8	12.9

1. AiResearch

a. TPE331

Profile

Prospects for meeting the 1979 standards:
HC, CO - good with category 1 technology by Jan. 1, 1979
NOx - already met
Equivalent shaft horsepower = 900 (-3 model)
PR = 10.4
Combustor type: reverse flow annular
Application: Fairchild Turbo Porter, Short Skyvan, NAR Turbo Commander 690, etc.
Certification date: February '65 (-1 model)
Number delivered: unknown
Production rate: more than 60 per month for all models combined as of January '75
Production category after January 1, 1979: III

Effort Expended

AiResearch has conducted low emissions testing on the TPE-331 engine since 1973. The only quantitative financial data available is that from the EPA ambient effects contract (Ref. 83). Approximately 16,000 dollars were spent on developing the concept of rescheduling the fuel flow to operate on only primary atomizers during the taxi-idle mode. Emissions can be controlled to a level below the standards on the TPE-331 engine with this concept.

Other concepts that have been investigated for use on the TPE-331 engine are airblast fuel nozzles (2 configurations) and taxi-idle power setting (parametric study). Data quantifying the amount of money and manhours spent on these studies is not available.

Results and Status

As noted above, this engine has demonstrated the capability to meet the standards by the required date with category 1 technology. This was accomplished by rescheduling the fuel flow to operate on only the primary atomizers during the taxi-idle mode. The improved fuel atomization resulted in an increase in combustion efficiency which was sufficient to achieve the required HC and CO emission reductions. NOx was not a problem as the current production engine levels are sufficiently below the standards to offset the slight increase (due to increased combustion efficiency). The available results are summarized in the table below.

Status (-3 model)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		Jan. 1, 1979
Production		55	44	8.0		
Taxi-idle* power setting	1	2.3	15.0	15.7	3 (Fig. 58)	late 1978
Primary only at taxi-idle	1	3.6	12.8	8.9	5 (Fig. 58)	Jan. 1, 1979
Airblast	2	33	35	9.2	2 (Fig. 60)	mid 1980

Projections and Prospects

No further reductions in emissions are likely for this engine since AiResearch plans to implement the primaries only at idle concept. As noted above this concept controls emissions to a level below the standards. This concept is expected to be used in newly manufactured engines after January 1, 1979.

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*Best combination demonstrated was at 7 percent rated power at 100 percent rated speed.

2. Pratt & Whitney Aircraft of Canada

a. PT6A-27

Profile

Propsects for meeting the 1979 standards:
HC, CO - good with category 2 technology by late 1979
NOx - already met
Equivalent shaft horsepower = 715
PR = 6.5
Combustor type: reverse flow annular
Application: Beech 99A, DHC Twin Otter, etc.
Certification date: c. November '67
Number delivered: 1000 as of March '75
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

Available data (Ref. 20) indicates that low emissions testing began in 1973. Fiscal data is available for that year only, during which approximately 87,000 dollars were spent for low emissions research. Low emissions data reported indicates that only airflow redistribution techniques (category 2 technology) have been tested on this engine. At least five different engine tests of three different combustors were made to optimize the primary zone fuel-air ratio, delay quenching, and to improve mixing.

Results and Status

The PT6A27 has a relatively high surface-to-volume ratio (12.35 ft^{-1}), and a relatively low compressor discharge pressure (1.8 atm) and temperature (660 °R) at idle, all of which contribute to high HC and CO emissions. High surface-to- volume ratio combustors tend to have higher HC and CO emissions because of wall quenching effects. The low compressor discharge pressure compounds the problem by causing slow reaction rates.

Emissions levels below the standards have been demonstrated by this engine using a rich primary, delayed quench combustor. However, this combustor has a problem of very hot walls which will have to be resolved before it is flightworthy. Available test results are presented in the table below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		Jan. 1, 1979
Production		52	66	7		
Lean primary, delayed quench (avg. of 2)	2	4.9	22.9	No Data	3 (Fig. 60)	late 1979
Rich primary, delayed quench (avg. of 2)	2	2.0	19.0	8.1	3 (Fig. 60)	late 1979
Improved primary zone mixing, delayed quench	2	4.8	31.6	No Data	3 (Fig. 60)	late 1979

Projections and Prospects

This engine has demonstrated the capability of meeting the standards with the rich primary zone, delayed quench combustor. It is expected therefore that Pratt & Whitney of Canada will pursue development of this combustor. As noted above the problem of very hot combustor wall will have to be resolved. As a result emissions of HC and CO may increase, but it is not expected that the increase will be so large that the standards will be exceeded (see PT6A-41 Status).

b. PT6A-41

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with category 2 technology by late 1979
    NOx - already met
Equivalent shaft horsepower = 903
PR = 8.0
Combustor type: reverse flow annular
Application: Beech Super King Air 200
Certification date: c. 1973
Number delivered: more than 110 as of February '75
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

Data reported in Reference 20 indicates that low emissions testing on the PT6A-41 began in 1973. During 1973 approximately 102,000 dollars were spent on low emissions testing. No fiscal data is available for any other time period.

Low emissions data reported for this engine also indicates that only airflow redistribution techniques have been tested on this engine. Similar to the PT6A-27 case, four tests were conducted to optimize the primary zone fuel-air ratio, delayed quenching, and to improve mixing.

Results and Status

As with the PT6A-27 emissions levels below the standards have been demonstrated with the rich primary zone, delayed quench combustor. The hot combustor wall problem exists with this engine also, and will have to be resolved. Available test results are presented in the status table below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		Jan. 1, 1979
Production		54	81	7.2		
Improved wall cooling	2	30.4	44.9	7.5	3 (Fig. 60)	late 1979
Rich primary, delayed quench	2	1.8	16.6	8.3	3 (Fig. 60)	late 1979
Rich primary, delayed quench plus improved cooling	2	4.7	23.2	8.7	3 (Fig. 60)	late 1979
Hotter intermediate zone	2	3.8	21.4	8.6	3 (Fig. 60)	late 1979

Projections and Prospects

Since this engine has demonstrated the capability to meet the standards with the rich primary, delayed quench combustor it is anticipated that development of this combustor will be pursued. The data above indicates that improved cooling has been added to this combustor without exceeding the standards. Further development is still needed, however, as hot spots were still noted.

3. Avco Lycoming

a. LTP-101

Profile

Prospects for meeting the 1979 standards:
HC, CO - fair with category 1-2 technology by late 1977
- good with category 1-2 technology by early 1980
NOx - good with category 1-2 technology by late 1977
Equivalent shaft horsepower = 620
PR = 8.4
Combustor type: reverse flow annular
Application: Piaggio P168, Britten-Norman Islander
Certification date: end of '75
Number delivered: non - just certified
Production rate: unknown
Production category after January 1, 1979: IV

Effort Expended

Data reported by Lycoming (Ref. 35) indicates that evaluation of control techniques for reducing emission levels from the LTP-101 combustor have been studied for about four years. No quantitative fiscal data has been reported, however.

Initially, a basic combustor design was evaluated. Emissions testing indicated that this combustor has low efficiency at idle. Experimental developments involved combustion zone aerodynamic development (better mixing in the primary zone) and improved fuel injection techniques (improved pressure atomizers and airblast). Because FAA certification was scheduled for 1975 Lycoming claims time was not available to complete emission optimization of the design (Ref. 35), and a partially improved configuration was chosen as the certification configuration since it had accumulated enough endurance experience.

Results and Status

The certification configuration fails to meet any of the 1979 standards. Overboard air bleed at taxi-idle and higher idle speed will help reduce HC and CO emissions further, but not sufficiently to reduce the 1975 certification configuration below the standards according to Lycoming estimates (Ref. 35).

A summary of the status of this engine is presented below.

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		
Basic design		17.9	44.1	5.3		
'75 cert. config.	1-2*	9.8	34.7	4.8	8 (Fig. 58,60)	mid 1977, or late 1977
Final config. (estimated by Lycoming)	1-2*	4-5	23-26	6-7	8 (Fig. 58,60)	mid 1977,** or late 1977**

Projections and Prospects

A development configuration (category 1-2 technology) with lower HC and CO emissions has been demonstrated. Since this combustor produces emissions below the standards (see table below) it seems that more effort should be made to produce a flightworthy version of this combustor. Lycoming has indicated that durability may be a problem with this combustor. The emissions from this combustor are tabulated below.

Status
(development configuration)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		
1975 develop. configuration	1-2	3.6	17.5	6.2	2 (Fig. 58,60)	early 1979 or early 1980

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*It is not known if these configurations include airblast fuel nozzles.

**Lycoming claims 5 years are needed for development, certification, and service evaluation.

b. T5321A

Profile

Prospects for meeting the 1979 standards:
HC, CO - already met
NOx - already met
Equivalent shaft horsepower = 1800
PR = 8.0
Combustor type: reverse flow annular
Application: military
Certification date: not yet certified
Number delivered: unknown
Production rate: unknown
Production category after January 1, 1979: III

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		Jan. 1, 1979
Production		2	17	6.0		

c. PLT27

Profile

Prospects for meeting the 1979 standards:
HC, CO - already met
NOx - already met
Equivalent shaft horsepower = 2000
PR = unknown
Combustor type: folded annular
Application: military
Certification date: not yet certified
Number delivered: still in development
Production rate: still in development
Production category after January 1, 1979: IV

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		Jan. 1, 1979
Production		0.3	3	12.8		

Comment

Current production models of both the T5321A and PLT27 engines meet the standards. No other low emissions data was reported. Apparently no effort has been conducted to lower the emissions presumably because these engines already meet the standards, and also because these two engines currently have military applications. They are included here to indicate the low emissions levels that have been achieved in other Lycoming engines. Possibly this technology may be applicable to the LTP-101 or ALF-502 engines.

4. Allison

a. 250

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with category 2 technology by late 1979
    NOx - already met
Horsepower = 400 (-B17 model)
PR = 7.2
Combustor type: single can
Application: Turbostar 502
Certification date: September '65
Number delivered: unknown
Production rate: "small quantities" according to Allison
Production category after January 1, 1979: III

Effort Expended*

Data reported in Reference 57 indicates a total of 1,145,000 dollars was spent by Allison on the 250 low emissions effort for the time period 1971-1975. Of this total 65% (745,000 dollars) was government funds.

The only low emissions data available for this engine is that which was developed under contract with the U.S. Army Air Mobility Laboratory. During this one year program, approximately 97,000 dollars were spent evaluating seventeen low emissions combustors. Each combustor incorporated one or more of the following concepts (grouped by combustor area affected):

- fuel injector
  - air blast/air assist
  - premix/prevaporization
  - staged
- . primary zone
  - lean
  - rich
  - variable geometry
  - early quench
  - reverse flow
  - massive recirculation
  - swirl
  - heat rejection
  - water injection
  - cold air injection
- . primary dilution zone
  - increased length
  - double combustor volume
  - rapid plug flow

Results and Status

The premix combustor has demonstrated the capability of controlling exhaust emissions to a level below the standards. It is expected that this is the combustor concept that Allison will use to reduce emissions from the 250 engine. It should be noted that this combustor increased NOx by 75 percent relative to the production combustor. However, NOx remained below the standard. The emissions of the premix combustor are presented below.

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*It should be noted that data reported in Reference 57 indicates that 1,633,000 dollars were spent by Detroit Diesel Allison on aircraft turbine engine related technology programs during the period 1970-1975. Of this total 1,088,000 dollars (67%) were government funds.

Status (-B17 model)

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		
Production		25	128	5.3		
Premix combustor	2	1.2	13.8	9.3	3 (Fig. 60)	late 1979*

Projections and Prospects

It is expected that Allison will continue development of the premix combustor and use it in the 250 engine. No known development problems exist with this combustor.

b. 501

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with category 2 technology by mid 1980
    NOx - already met
Horsepower = 400 (-D22A model)
PR = 9.5
Combustor type: multiple cans
Application: Lockheed Hercules
Certification date: c. 1968 (-D22A model)
Number delivered: 11,000 (756 and 501 engines combined) for aircraft and industrial use
Production rate: 3300 during next 10 years
Production category after January 1, 1979: II, III

Effort Expended

Financial data reported to the EPA (Ref. 57) indicates that 2,423,000 dollars were spent during the time period 1970-1975 on 501 low emissions work. Sixty-one percent (1,485,000 dollars) were provided by the government.

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*Allison claims that 5-6 more years are needed to produce this combustor.

The 501 engine was selected by NASA for the Class P2 portion of their Pollution Reduction Technology Program (PRTP). This effort was initiated in January 1975 and ended in February 1976. Approximately 242,000 dollars were spent on a cost share basis, Allison supplying 33% and NASA, 67%. This program is the source of the only low emissions data reported for this engine.

A total of 18 configurations of three basic low emissions combustor concepts were tested. These are 1) the reverse flow combustor, 2) the prechamber combustor, and 3) the staged fuel combustor. A description of these concepts is given below.

1) The reverse flow combustor - This reverse flow combustor is not the reverse flow annular type used in such engines as the TFE-731, the JT15D, and the ALF-502. This reverse flow combustor is a can type and incorporates a primary zone flow system which increases the amount of recirculating products, improves fuel-air mixing, and returns the partially burned products trapped in the cooling film, back into the reaction. The remainder of the combustor is of conventional design. It should be noted that each of the five combustor configurations of this type incorporated either airblast or air-assist fuel nozzles.

2) The prechamber combustors - This type of combustor is called premix-1 by the EPA and is described in part 13 of Appendix C. In this program a total of six configurations of two basic designs were tested. These designs were: a) a short prechamber combustor where fuel and air are mixed but do not burn, and b) a long prechamber which does act as a small combustor. Two noteworthy features of both designs are the airblast fuel nozzles, and a variable geometry band used to open and close dilution holes (the latter device will not be incorporated into flight hardware as its main purpose was parametric investigation of airflow distribution).

3) The staged fuel combustor - Fuel staging is described in part 15 of Appendix C. A total of seven configurations of two basic designs were tested. These were: a) an original staged combustor design, and b) a modification of the original design. The original design incorporated features to produce minimum HC and CO emissions. (No attempt to control NOx was made since an increase in NOx was allowed.) This was accomplished by providing for a lean pilot zone, low pilot zone airflow loading, reduced wall quenching, a reverse flow feature in which CO and HC in the dome cooling are returned to the reaction, and a swirl prechamber which provides good fuel-air mixing in the combustion zone. The modified combustor was designed to reduce CO further and reduce NOx. This combustor had an increased pilot zone volume, and a reduced pilot zone equivalence ratio.

No other low emissions testing has been reported on the Allison 501 engine.

Results and Status

All of the basic designs selected were capable of controlling all of the emissions to levels below the standards. The reductions of HC and CO achieved were substantial; however, NOx generally increased relative to the production combustor level. According to NASA (Ref. 34) the performance characteristics of all the configurations were acceptable and the measured exit temperature pattern factors were better than the baseline combustor. The emissions of the best configuration of each design are presented below.

Status (-D22A model)

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		
Production		14	30	6.2		
Reverse flow mod IV	2	0.3	4.6	7.3	2 (Fig. 60)	mid 1980
Prechamber mod III	3-4	0.4	2.1	8.5	2 (Fig. 62)	late 1981
Staged fuel mod V	3	0.6	5.7	7.2	2 (Fig. 62)	late 1981

Projections and Prospects

It is expected that Allison would pursue development of one of the above designs for the 501 engine, probably the reverse flow concept since it is the least complex. No development problems have been reported for any of these designs.

5. Rolls Royce

a. Dart

Profile

Prospects of meeting the 1979 standards:
HC, CO - poor by late 1978
- fair by mid 1979
NOx - good by late 1978
Equivalent shaft horsepower = 2280
PR = 5.75
Combustor type: multiple cans
Application: Grumman Gulfstream I, Fairchild F-27
Certification date: c. April '53
Number delivered: 6500 as of January '75
Production rate: 50 per year halfway through the next decade
Production category after January 1, 1979: I

Effort Expended

No fiscal data quantifying the effort expended on low emissions testing on the Dart engine has been reported. Further, the only low emissions data available for this engine are the EPAP values achieved by using duplex fuel nozzles in the combustor.

Results and Status

The duplex nozzles reduced HC, CO and NOx, but only NOx was controlled to a level below the standards. The status of the Dart is presented below:

Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		
Production		100	125	<12.9		
Duplex nozzles	1	66	95	1.4	3 (Fig. 58)	late 1978

Projections and Prospects

The levels of HC and CO listed above are very much higher than the standards. If the fuel flow were scheduled to operate on the primary atomizers only during taxi-idle such as in the TPE331, and the percentage reductions in HC and CO, and the NOx increase were the same for the Dart as the TPE331 the EPAPs listed below would result.

Projected Status

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		4.9	26.8	12.9		
Primary atomizers only at taxi-idle	1	4.3	27.7	1.6	1 (Fig. 58)	mid 1979

These levels may be somewhat optimistic as the rated pressure ratio (and hence idle pressure ratio) of the Dart is lower than that of the TPE331-3 (5.75 compared to 10.4). Another rating 1 concept worthy of consideration is to increase the taxi idle speed. (The amount of CO reduction is a function of the amount of increase in taxi idle speed.) This should be especially effective for this low pressure ratio engine and could be done in conjunction with operating the primaries only.

It should be noted that at the January 1975 hearings Rolls Royce requested total exemption for this engine because of the limited production. Rolls Royce has estimated the production rate of the Dart at approximately 50 engines per year halfway through the next decade.

b. Tyne

Profile

Prospects for meeting the 1979 standards:
  HC, CO - unknown
    NOx - unknown
Shaft horsepower = 5500
PR = 13.5
Combustor type: straight flow annular
Application: Belfast, CL-44
Certification date: c. 1960
Number delivered: unknown
Production rate: unknown
Production category after January 1, 1979: I

Effort Expended

This engine is not included in the list of engines in Reference 44 for which reduced emissions programs are being conducted. Therefore probably no effort has been made.

Results and Status

No data, either production or reduced emissions, is available for this engine.

Projections and Prospects

It is not expected that Rolls Royce will make any effort to reduce emissions from this engine because of the remaining limited production of the engine.

F. Auxiliary Power Units

Auxiliary power units are defined as ". . . any engine installed in or on an aircraft exclusive of the propulsion engines." (See FR Vol. 38, No. 136, July 17, 1973, p. 19091.) These engines are used to provide onboard pneumatic energy for jet engine starting, air conditioning, heating and anti-icing. Shaft power is provided for generators and hydraulic pumps. The gaseous emissions standard listed below for these engines is currently scheduled to go into effect on January 1, 1979.

Standard

EPAP
(lbs pollutant per 1000 horsepower-hours at maximum power)

HC	CO	NOx
0.4	5.0	3.0

Certain common design characteristics of APUs, coupled with the nature of the EPA standard, have created difficulties for APU manufacturers attempting to comply with the standards. The first characteristic is that APUs have in general been designed with low operating pressure ratios, despite the SFC penalty incurred. The reasoning behind this is threefold: (1) the pneumatic systems cannot take over 3-4 atmospheres for operation; (2) the total fuel requirements of the APU are much less than that of the main engines in the aircraft and, therefore, it is more economical to design for low initial and low maintenance costs (i.e. low sophistication, in particular, low pressure ratios) than to design for better fuel economy with more sophistication; and (3) for many APUs which are fairly small, a higher pressure ratio would mean exceedingly small components in the high pressure segments leading to excessive efficiency penalties.

The second characteristic is that being small engines in general, many APUs have been built with reverse flow annular combustors (because of the use of radial flow turbomachinery which retains better efficiency on the small scale than does axial flow machinery). This results in two problems: The first is that the surface-to-volume ratios of such combustors are fairly high, leading to a propensity for high emissions of HC and CO (See Section III); the second is that any attempts to incorporate a fuel staging scheme into the combustor to control NOx meet with difficulty because of the limited space available.

The third characteristic is that APU operation is not consistent with the low emissions technical development which has been directed towards the cycle type of operation of the propulsion engines. For the APUs, the test condition is at a specific power point (maximum combined shaft plus air bleed) and consequently some of the less complex (category 1) concepts used to control HC and CO, such as increased idle speed, compressor bleed changes, etc., are simply not relevant.

Another problem is that even water injection for NOx control is not technically feasible in all cases; it creates a number of complications which compromise its usefulness. In particular, the bulk of the NOx production is not limited to particular modes as is the case for propulsion engines, but is uniformly distributed throughout the operation "cycle" of the APU. This implies that water must be used at all times if it is to be used at all. As replenishment of the water is not available immediately upon landing and may often not be available at all, it then follows that water must be carried on board throughout the flight. The additional tankage and weight create economic penalties and the need to prevent freezing of the water requires further care. Mixing water with methanol compromises CO control even more as the quenching effect of the water and the generally low operating pressure lead to incomplete combustion of the anti-freeze. Even straight water, in fact, in some APUs (notably the low pressure ones) leads to excessive quenching of the flame and, therefore, high HC and CO.

1. AiResearch

AiResearch has tested a variety of emission control techniques that could be utilized for APU emissions reduction. These techniques have been largely tested and evaluated on the GTCP85 APU or on a rig with conditions simulating that APU. However, as many of these concepts are applicable to any of the other AiResearch APUs and as the test results can be extrapolated, AiResearch avoided repetitive testing of the same concept in each engine unless it showed promise in the first instance. As the concepts explored by AiResearch can thus be considered to be relevant to each of its engines, it is reasonable to discuss the issue of effort expended (in terms of technology exploration) in general terms prior to the discussion of each engine.

Effort Expended

By and large, the concepts investigated by AiResearch have been able to meet the HC and CO standards, while the preliminary investigations of category 3 concepts yielded no improvement in NOx. Water injection (category 2), tested as an alternative to category 3 complexity, creates problems in its own right (as discussed earlier).

The techniques explored by AiResearch since 1973 are categorized into four main groups with the specific concepts listed under each. These are as follows:

I. Fuel preparation

1. Airblast (category 2) - A series of tests were made on a research combustor to investigate the potential of the pure and piloted airblast nozzle and the air-assist nozzle. A total of eleven tests of different injectors were made on a total of seven different combustor airflow distributions or mixing schemes for a grand total of 77 configurations. Subsequently a piloted airblast system was investigated in both GTCP85 rig and engine testing with three different combustor airflow redistributions, and an air-assist/airblast injector was checked in a GTCP36 rig with several modifications to the airflow pattern.

2. Air-assist (category 1) - This concept was investigated to the extend described in the airblast discussion above.

3. Premix/prevaporization (category 3-4) - Two different concepts were explored, both using the GTCP85 rig. The first was a "scroll" combustor which acted like a carburetor mechanism. Seven test conditions were run on a single scroll configuration. The second was a more conventional prechambered combustor and it was evaluated at eleven test conditions.

II. Fuel distribution

1. Fuel staging (category 2-3) - A single staging configuration was explored in the GTCP85 rig. The combustor involved two axially seperated fuel injection localities within a single combustor (i.e., the two primary zones were not mechanically separated). A parametric study (8 points) of the optimal staging ratio was done.

2. Fuel atomizer design (category 1) - Three types of changes were investigated over the APU operating range, injection, pressure, distribution of fuel between the orifices (dual orifice nozzle), and change in the spray angle.

III. Air distribution

1. Lean primary zone (category 2) - This concept was explored in the parametric studies of other concepts (e.g., airblast).

2. Increased turbulent mixing (category 2) - This concept was explored in the parametric studies of other concepts.

3. Improved uniformity in the primary zone (category 2) - Attempts to improve combustion through a more thorough investigation of the effect of bleed port location (three tested) and of a lengthened combustor (eight tested).

IV. Water injection (category 2) - While only one water/fuel ratio was investigated (= 1), two injection points were checked, compressor inlet and primary zone, as were two mixtures, pure water and water-methanol solution for anti-freeze capability. Water injection was tried in both the GTCP85 combustor and in the TSCP700 combustor.

In addition, AiResearch ran a large number of tests on various production type APU engines to determine the effects of production tolerances, fuel variability, ambient effects, and oil seal leaking, in order to better define the compliance problem.

Data quantifying the amount of dollars or manhours spent on any of this testing has not been reported to the EPA.

The discussion will continue now with an engine-by-engine analysis, including profiles, results and status, and projections and prospects.

a. GTCP 85

Profile

Prospects for meeting the 1979 standards:
HC, CO - good with either category 1 or 2 technology by 1979
NOx - poor with category 3 technology
Bleed air horsepower = 177-216
Shaft horsepower = 25-100
PR = 3.2-3.5
Combustor type: single can
Application: B727, DC-9, B737, BAC 111 etc.
Certification date: c. 1960
Number delivered: approximately 2500 as of mid '75
Production rate: unknown
Production category after January 1, 1979: III

Results and Status

Below are tabulated most of the concepts explored on the GTCP 85 or rig equivalent in the AiResearch APU study.

Status

Concept	Technology Category		EPAP		Development Status (Task No.)	Implementation Date
		HC	CO	NOx		
Standard		0.4	5.0	3.0		
Production		0.2	7.5	6.4		
Air-assist	1	Claimed to be similar to air-blast. No EPAPs available.			2 (Fig. 66)	mid 1978
Atomizer design						
-narrow spray	1	0.6	9.6	6.2	3 (Fig. 66)	early 1978
-wide spray	1	0.1	3.7	6.9	3 (Fig. 66)	early 1978
Airblast	2	0.1	3.9	6.7	4 (Fig. 67)	mid 1978
Lean primary zone	2	Claimed there is no improvement for APUs. No EPAPs available.			4 (Fig. 67)	mid 1978
Increased turbulent mixing	2	0.1	5.1	7.9	4 (Fig. 67)	mid 1978
Water injection - standard nozzles at -H_2O/fuel = 1.0	2	0.8	19.4	2.9	4 (Fig. 67)	mid 1978
airblast nozzles at -H_2O/fuel = 1.0	2	2.0	15.0	2.7	4 (Fig. 67)	mid 1978
Fuel staging	3	0.1	4.0	9.2	2 (Fig. 68)	mid 1980

Projections and Prospects

There are several possible approaches to compliance with the HC and CO standards, but none apparently for compliance with the NOx standard as even water injection is creating an unacceptable HC and CO penalty from quenching. On the other hand, it is not at all obvious that a staging technique cannot be better than has been demonstrated to date despite the obvious technical problems.

b. TSCP 700

Profile

Prospects for meeting the 1979 standards:
  HC, CO - already met
    NOx - good with water injection (category 2) by 1979
      - good with category 3 by 1981
Equivalent shaft horespower = 910
PR = 10.4
Combustor type: reverse flow annular
Application: DC-10, A300
Certification date: c. 1971
Number delivered: approximately 250 as of early '75
Production rate: unknown
Production category after January 1, 1979: III

Results and Status

The TSCP 700 benefits from a relatively high compressor pressure ratio at its operating condition which is reflected in the low HC and CO emissions of the production engine; it is also reflected in the adequate HC and CO emissions performance even with water injection. This higher pressure ratio engine is probably typical of the new design approach to be taken in the future (see also the ST6 APU below).

Status

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Production		0.2	0.8	6.0		
Water injection	2	No data	1.6	3.0	4 (Fig. 67)	mid 1978

Projections and Prospects

With nothing more than the use of water injection, the TSCP 700 can comply with the standards. However, water injection is not a particularly acceptable solution because of the need to carry water aboard and to prevent it from freezing. Category 3 techniques have not been tried in the 700 as yet and, for that matter, they are just now being investigated in reverse flow annular combustors (in the TFE 731) as a part of the NASA Pollution Reduction Technology Program. On the basis of the preliminary results of the TFE 731 testing, the following projection for category 3 performance has been made:

Projected Status

Concept	Technology Category	EPAP HC	CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Premix/prevap.	3	-	-	1.7	2 (Fig. 68)	late 1980

It is important to realize that this projection can be made because the TFE731 and the TSCP700 have the same type of combustor. Unfortunately, no such projections can be made between engines of different combustor types.

c. GTCP 36

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with category 2 technology by 1979
    NOx - unknown
Shaft horsepower = 192
PR = 3.25
Combustor type: single can
Application: F-28, Gulfstream 11, YS-11, G-222
Certification date: c. 1967
Number delivered: approximately 250 as of mid '75
Production rate: unknown
Production category after January 1, 1979: III

Results and Status

The production combustor of the GTCP 36 engine uses an air-assist airblast fuel nozzle. Several rig and engine tests were conducted to determine the emissions levels produced by this combustor during development. The best demonstrated emissions along with the production engine emissions are shown in the table below.

Concept	Technology Category	EPAP HC	CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Production		0.3	19.8	5.2		
Airblast	2	0.04	<5.0	5.4	4 (Fig. 67)	mid 1978

Projections and Prospects

Airblast is apparently the way that AiResearch will handle HC and CO control. The test data suggest that this is unusually effective in this engine (compare with the GTCP 85 data). NOx control would require water injection as there is yet no category 3 technology that has been successfully demonstrated in a can combustor type APU. However, as water injection has not actually been demonstrated in this engine, it's effect on the CO level, in particular, is in question.

d. GTCP 30

Profile

Prospects for meeting the 1979 standards:
  HC, CO - already met
    NOx - unknown
Shaft horsepower = 100
PR = 3.76
Combustor type: single can
Application: DC-7, Jet Star, etc.
Certification date: unknown
Number delivered: unknown
Production rate: unknown
Production category after January 1, 1979: II

Results and Status

No emissions work has been done on this engine:

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Production		0.1	4.8	3.4		

Projections and Prospects

The manufacturer intends to stop production of this APU (reference 14, p. 2-11) and replace it with the GTCP 36-50. The production configuration already meets the HC and CO standards and the NOx level is close. If water injection were to be attempted to reduce the NOx level to that of the standard, it is conceivable that something would have to be done about the increased CO level. Even with the problem of water injection, the CO level is marginal and the need for a greater statistical margin would require some correction. The airblast concept tested on both the GTCP 85 and the GTCP 36 was quite successful and is relatively easy to incorporate. The following EPAPs are projected if that concept were tried in the GTCP 30:

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Airblast	2	0.01- 0.05	1.2- 2.5	3.5- 3.6	2 (Fig. 67)	mid 1979

e. GTCP 660

Profile

Prospects for meeting the 1979 standards:
  HC, CO - good with category 2 technology by mid 1979
    NOx - poor with category 2 technology;
      - fair with category 3 technology by 1981
Equivalent shaft horsepower = 1100
PR = 3.5
Combustor type: straight flow annular
Application: B747
Certification date: c. 1969
Number delivered: approximately 300 as of mid '75
Production rate: unknown
Production category after January 1, 1979: II, III

Results and Status

No emissions work has been done on this engine to EPA's knowledge due in part to the conviction by the manufacturer that the post-1979 production will be inadequate to justify the development expense.

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Production		0.2	7.9	4.9		

Projections and Prospects

The manufacturer may hope to obtain relief through a waiver or a change in the standards rather than undergo the possibly unrecoverable expense of developing a low emissions combustor for the 660 just when the production rate of the Boeing 747 would be in its decline. Just what Boeing would do for an APU in the event of the unavailability of the 660 is uncertain. On the other hand, based on all of the available test results from the GTCP 85 and the GTCP 36 APUs, it appears that HC and CO emissions can be controlled on the engine to a level below the standards by using the airblast fuel nozzles.

The projected values are:

Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Airblast	2	0.03-0.1	2.0-4.1	5.1	2 (Fig. 67)	mid 1979

If this were combined with water injection, however, it is not certain that the CO level, in particular, would remain below the standard (see the GTCP 85 and TSCP 700 data). Alternatively, as this is a straight flow annular combustor, it is possible that some of the category 3 concepts which have been tested on propulsion engines having the same style combustor may also be applicable here. Due to the smaller size of this engine, though, it is not possible to make meaningful projections as to the reductions of any of the pollutants.

2. Pratt & Whitney Aircraft of Canada

a. ST6

Profile

Prospects for meeting the 1979 standards:
HC, CO - already met
NOx - poor with category 2 technology;
- good with category 3 technology by 1981
Shaft horsepower = 720
PR = 7.8
Combustor type: reverse flow annular
Application: L-1011
Certification date: c. 1979
Number delivered: approximately 200 as of early '75
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

No emission data either from current production or reduced emissions concepts has been submitted to the EPA. However, as this engine is directly derived from the PT6 turboprop/turboshaft series; it may be surmised that the manufacturer intends to rely on his low emissions work on the PT6 to solve any problems relating to the ST6.

Results and Status

The status of this engine was estimated from PT6A-41 data, employing the best category 2 concept which has been investigated in the PT6.

			EPAP			
Concept	Technology Category	HC	CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Production		0.3	2.6	4.8		
Airflow distribution	2	0.02	1.0	5.2	3 (Fig. 67)	late 1978

Projections and Prospects

Both the production and the airflow redistribution concepts control HC and CO to a level below the standards. However, NOx remains high as in other APUs. Fuel staging or premix/prevaporization concepts may help to reduce NOx because of this engine's relatively high compressor pressure ratio (7.8). The only category 3 concepts that have been investigated on a reverse flow annular combustor such as this engine have been those tested on the TFE 731 as a part of the NASA Pollution Reduction Technology Program. The following emissions projection is made for the ST6 using that technology:

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Premix/prevap.	3	-	-	1.3	2 (Fig. 68)	late 1980

It is worthwhile to note that any category 3 concept for this engine must be written off completely against the APU version as the turboprop version already meets the NOx standard. It is, in fact, interesting that the same basic engine can comply in the P2 class, yet with the same high power operating conditions, fail to meet the APU class standard.

3. Solar

a. Titan-39

Profile

Prospects for meeting the 1979 standards:
HC, CO - unknown
NOx - unknown
Shaft horsepower = 40
PR = 3.0
Combustor type: single can
Application: business jets
Certification date: unknown
Number delivered: unknown
Production rate: unknown
Production category after January 1, 1979: III

Effort Expended

The only data available for this engine is production engine emissions based on testing conducted in 1973. No improved combustor technology data has been reported. Solar has stated (Ref. 60), however, that major redesigns of the combustion system are anticipated in order to meet the standards.

Results and Status

Concept	Technology Category	HC	EPAP CO	NOx	Development Status (Task No.)	Implementation Date
Standard		0.4	5.0	3.0		
Production		0.6	21.0	4.4		

Projections and Prospects

Nothing is known.

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51. Control of Air Pollution from Aircraft Engines, January 27, 1976, National Business Aircraft Association, Inc. Submission to the EPA Public Hearings on Aircraft Emissions, Jan. 1976.

52. Statement by C.F. Von Kann, Senior Vice President - Operations and Airports, Air Transport Association of America, January 28, 1976. Submission to the EPA Public Hearings on Aircraft Emissions, Jan. 1976.

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54. Letter from V.L. Blumenthal (Boeing) to Deputy Assistant Administrator, Office of Mobile Source Air Pollution, EPA, dated January 20, 1976. Subject: Comments on Pollutant Emission Standards for Aircraft Turbine Engines.

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57. Letter from T.M. Fisher (GM) to J. Cerar (EPA) dated Feb. 25, 1976. Subject: Supplement to Statement presented by GM at January Hearings.

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76. Letter from D. W. Bahr (GE) to Gary Austin (EPA) dated January 14, 1975 Subject: CFM56 Emissions Data.

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80. Letter from G. Opdyke (AVCO Lycoming) to R. Sampson (EPA) dated Jan. 8, 1974 Subject: Emissions Data.

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Appendix A

PROGRAMS FOR REDUCTION OF ENGINE EMISSIONS

This appendix summarizes all the programs known to the EPA which bear upon the compliance of aircraft gas turbine engines with the EPA regulations. These programs are broken into two categories, engine related programs and combustor research programs. The former are directed exclusively towards the 1979 EPA standards and the latter are applicable to all the standards in general as such programs serve more to advance understanding than to concoct a specific solution.

Engine Related Programs

Government Sponsored Engine Programs

The government has sponsored and continues to sponsor several major engine related low emissions combustor development programs. A summary of these programs is provided in Table A-1. Research and development in these programs were conducted by private companies, and in some cases the company partially funded these programs on a cost sharing basis.

Industry Sponsored Engine Programs

Most of the manufacturers have initiated programs of their own to identify and refine the technology necessary to satisfy the 1979 standards. In general two approaches were taken. These were modification to current production hardware, and new combustor design concepts. Again, as indicated above, some of these programs were conducted on a cost sharing basis with the government. A summary of these programs is provided in Table A-2.

Table A-1

Engine Related Programs - Government Sponsored

Agency/Company	Objective	Status	Funding/Duration
NASA Lewis/Garrett AiResearch (Small Jet Engine Program)	Demonstrate combustor technology, for the TFE 731 engine, which is capable of meeting T1 class standards.	Phase I (combustor screening of three phases is essentially completed. The combustor concepts being screened are: 1) modified existing combustor 2) airblast system (meets HC and CO standard) 3) premix/prevaporization (meets HC, CO and NOx standard)	693K Phase I /FY 75-76 (17 months)
NASA Lewis/Pratt & Whitney Aircraft (Can-Annular Program)	Demonstrate combustor technology, for the JT8D engine, which is capable of meeting the T4 class standards.	Phase I (combustor screening) is completed and the report published. The second phase has been cancelled. The combustor concepts screened were: 1) modified existing combustor (meets HC standard) 2) vorbix combustor 3) premix/prevaporization	513K Phase I /FY 75-76 (16 months)
NASA Lewis/Detroit Diesel Allison (Turboprop Program)	Demonstrate combustor technology, for the 501D-22 engine, which is capable of meeting the P2 class standards.	Phase I (combustor screening) of three phases is completed, and the report published. The combustor concepts screened were: 1) reverse flow 2) staged fuel 3) prechamber (meets HC, CO, NOx standard)	242K Phase I /FY 75-76 (13 months)
NASA Lewis/General Electric (ECCP)	Demonstrate combustor technology, for the CF6-50 engine, which is capable of meeting the 1979 T2 class standards.	Phase III (engine demonstration) of three phases is approximately 70 percent complete. Pursuing double annular combustor concept. (Meets: HC, CO standards) (Fails: NOx standard)	1000K Phase I /FY 73-74 (18 months) 950K Phase II /FY 75 (12 months) 1200K Phase III /FY 76 (12 months)
NASA Lewis/Pratt & Whitney Aircraft (ECCP)	Demonstrate combustor technology, for the JT9D engine, which is capable of meeting the 1979 T2 class standards.	Phase III (engine demonstration) of three phases is nearly completed. Pursuing vorbix combustor concept. (Meets: HC, CO, NOx standards)	800K Phase I /FY 73-74 (19.5 months) 950K Phase II /FY 75 (12 months) 1200K Phase III /FY 76 (14 months)
Army/Detroit Diesel Allison	Develop and demonstrate technology sufficient to obtain a 50 percent overall reduction in T63 (class P2) engine emissions with no increase in any individual pollutant.	Program completed. Best concept is the premix combustor. (Meets: HC, CO and NOx Standards)	97K/FY 72-73 (12 months)

Table A-1 continued

Agency/ Company	Objective	Status	Funding/Duration
Army/Williams Research **/Garrett AiResearch** **/Pratt & Whitney Aircraft** **/AVCO Lycoming**	Develop new high performance turboshaft engines with low emissions. Engine has application as turboprop (class P2) or as an APU.	Program nearing completion Williams concept - meets standards AiResearch concept - fails standards Pratt & Whitney concept - no data AVCO Lycoming concept - meets standards	Unknown
Army/Detroit Diesel Allison	Refine best designs and concepts from T63 program above and test in a Model 250-C-20B (class P2) engine.	Testing has been completed and data is in final stages in preparation for report. No data published as yet.	293K/FY 74-76 (23 months)
EPA/Garrett AiResearch	Develop full scale engine data to determine the effects of ambient conditions on emissions for the TPE331 (Class P2) and GTCP85 (APU) engines.	Testing has been completed and a final report is being prepared. The emissions standards were achieved in the TPE331 engine by rescheduling the fuel flow to operate only on primary atomizers at taxi-idle.	Joint project 170K TPE331 extension 16K FY75-76(10 months)

Table A-2

Engine Related Programs ~ Industry Sponsored

Company	Objective	Status	Funding/Duration
Garrett AiResearch	Develop combustor technology for the TPE 331 engine which allows it to meet P2 class standards.	Best concept is rescheduling fuel flow to operate on the primary atomizers only at taxi-idle. (Meets: HC, CO, NOx standards)	Unknown/1973-1974 (2 Years)
Garrett AiResearch	Develop combustor technology for the TFE 731 engine which allows it to meet T1 class standard.	Best concept demonstrated was the air assisted fuel nozzles.	
Garrett AiResearch	Develop combustor technology for APUs which allow them to meet the APU standard.	Best concepts demonstrated were: GTCP 36 - airblast - meets HC and CO standard; fails NOx GTCP 85 - increased fuel spray cone angle - meets HC and CO standard; fails NOx GTCP 30 - } production combustor - TSCP 700 } meets HC and CO stan- dard; fails NOx GTCP 660 - production combustor - meets HC standard; fails CO and NOx	
Garrett AiResearch (Small Jet Engine Program)	Demonstrate combustor technology for the TFE-731 engine, which is capable of meeting the T1 class standards	See Table I	Cost shared with NASA Company share unknown See Table I
Pratt & Whitney Aircraft	Develop combustor technology for the JT9D engine which allows it to meet 1979 T2 class standards.	Best concept demonstrated was aerating fuel nozzles combined with modified airflow distribution. (Meets: HC, CO standards) (Fails: NOx standard, unless water is used.)	Unknown/1972-1975 (3 Years)
Pratt & Whitney Aircraft (ECCP)	Demonstrate combustor technology for the JT9D engine which is capable of meeting the 1979 T2 class standards	See Table I	Cost shared with NASA Company share unknown See Table I
Pratt & Whitney Aircraft (Can-Annular program)	Demonstrate combustor technology for the JT8D engine which is capable of meeting the T4 class standards.	See Table I	Cost shared with NASA Company share unknown See Table I
Pratt & Whitney Aircraft	Develop low smoke combustor for JT3D (class T3) engine.	Best concept demonstrated combined delayed dilution with aerating fuel nozzles. This concept significantly reduced HC and CO while increasing NOx. (Fails: HC, CO, NOx standards)	Unknown/1968-1974 (6 Years)

Table A-2 continued

Company	Objective	Status	Funding/Durations
Pratt & Whitney Aircraft		JT12A class T1 engine is expected to be out of production and therefore no effort was made to reduce emissions from it.	
United Aircraft of Canada Limited	Develop low emissions combustor technology for the PT6A-27 and -41 (class P2) engines	The best emissions results were obtained with the combustor airflow redistributed. Results were: PT6A - 41 - meets HC, CO, and NOx standard PT6A - 27 - meets CO and NOx standard; fails HC	190K/1973 (1 Year)
United Aircraft of Canada Limited	Develop low emissions combustor technology for the JT15D (class T1) engines	The most effective concept demonstrated was 10% compressor bleed at idle and approach. (Fails: HC, CO, NOx standards)	255K/1971, 1973 (2 Years)
General Electric	Determine the most effective method of reducing emissions in the CJ610/CF700 (class T1) engines	Reducing the fuel spray cone angle was the most effective concept demonstrated. With this method HC levels were reduced 60 percent relative to current engine (still fails to meet standard) while NOx remained acceptable (meets standard) and CO was unchanged (fails to meet standard).	Unknown/1973-1974 (2 Years)
General Electric (ECCP)	Demonstrate combustor technology for the CF6-50 engine, which is capable of meeting the 1979 class T2 standard.	See Table I	Cost shared with NASA Company share unknown See Table I
Detroit Diesel Allison (Turboprop Engine Program)	Demonstrate combustor technology for the 501D-22 engine, which is capable of meeting the P2 class standards.	See Table I	Cost shared with NASA FY 75-76 Company share 81K Phase I (13 mos.) See Table 1

Combustor Research Programs

Government Sponsored Combustor Research Programs

Several non-engine related combustor development programs have also been sponsored by the government. These programs include grants to private industry, research laboratories and universities, and NASA and Air Force "in-house" programs. A summary of these programs is provided in Tables A-3, 4, and 5.

Also, the government has sponsored a number of analytical combustor modeling studies to support the development of necessary low emissions technology. These studies have also been conducted by private industry, research laboratories and universities, and NASA and the Air Force. A summary of these programs is provided in Tables A-6, 7, and 8.

Industry Sponsored Combustor Research Programs

Although such efforts certainly exist within the industry, the EPA has no explicit knowledge of them, perhaps because they may be appendages to larger engine related programs.

Table A-3

Government Sponsored Combustor Development Program

Private Industry Non Engine Related

Program/Sponsoring Agency	Investigator	Objective	Status	Funding
Augmentor Emission Measurement Program/USAF	General Electric Company	Develop methods for determination of the emissions levels of afterburning engines	Program completed.	690K FY 73-75
Augmentor Emissions Reduction Technology/NASA Lewis	General Electric Company	Reduce emissions from duct burning engines	Approximately 80 percent complete	500K FY 75-76
Advanced Concepts to Reduce NOx in Aircraft/NASA Lewis	Solar Division of International Harvester	Reduce NOx at supersonic cruise conditions	Program completed.	250K FY 74-75
Low NOx Emission Combustor/NASA Lewis	General Applied Science Laboratory	Demonstrate that premix concept will result in low NOx at supersonic cruise conditions.	Program completed.	78K FY 74 75K FY 75 40K FY 76
Full Annular Low NOx Emission Combustor/NASA Lewis	Solar Division of International Harvester	Investigate application of jet-induced-circulation combustor concept to full annular combustor	Single source RFP has been issued.	
Fundamental Low Power Emission Study/NASA Lewis	General Electric Company	Study advanced concepts for reducing low power emissions that will permit the design of combustors meeting the 1981 standards.	Contract just signed.	300K FY77+
Combustor Exhaust Odor Intensity and Character Study/NASA Lewis	A. D. Little	To determine the intensity of odors of exhaust gases from various turbojet engines or combustors at several engine operating conditions, and to determine ambient odor intensities at strategic airport locations.	Program completed.	114K FY 72-73 25K FY 74-75
Supersonic Cruise Combustor Pollution Technology/NASA Lewis	Pratt & Whitney Aircraft General Electric Company	To investigate combustion concepts specifically designed for low NOx emission at supersonic cruise operating conditions. This is an addendum to ECCP.	Program completed.	200K to each investigator FY 73-74
Advanced, High-Temperature-Rise Combustor/AMRDL	Garrett AiResearch	Minimize NOx, CO, and HC and smoke levels for 2-5 lb/sec combustors at 12-16 atm inlet pressure	Project completed.	415K FY 70-73
Low Emission Jet Combustor/AMRDL	Jet Propulsion Laboratory	To generate and evaluate unconventional combustor design concepts.	Program is 60 percent completed.	Unknown
Low NOx Emission Combustor for Automobile Gas Turbine Engines/EPA-AAPS	United Aircraft of Canada Limited	Develop reduced emission and low fuel economy automotive gas turbine engine.	Project completed.	248K FY 71-74
Hydrogen Enrichment for Low Emission Jet Combustion/NASA Washington, D.C.	Jet Propulsion Laboratory	Experimentally evaluate the H_2-enrichment concept with a research combustor.	Currently, experimental evaluation of the H_2-enrichment concept is underway with a research combustor utilizing premixed H_2/fuel/air mixtures.	150K/year FY 73, 74, 75
Independent Research and Development/DOD	Engine contractors with DOD	Private industry is granted a limited amount of government funds to conduct independent research programs some of which will support low emissions studies		Unknown

Table A-4

Government Sponsored Combustor Development Programs

University Grants

Program/Sponsoring Agency	Investigator	Objective	Status	Funding
Mixing in High-Intensity Combustors/ NASA Lewis	Prof. R.A. Strehlow at University of Illinois	To develop means to probe molecular-level mixedness in high-intensity combustors	The effect of turbulence on molecular mixing is being investigated.	51K/year FY 73, 74, 75, 76
Flow Processes in Combustors/ NASA Lewis	F. Gouldin, S. Leibovich, F. Moore at Cornell University	Measure and predict velocity and turbulence levels in swirling recirculating flows with and without chemical reactions.	Several experiments in progress	64K FY 75 75K FY 76
Study of Techniques for Lean Combustion Systems/NASA Lewis	M. Branch, A. Oppenheim, R. Sawyer at University of California, Berkeley	Study combustion processes of fuel lean, turbulent flames at realistic gas turbine conditions to develop stabilization techniques and improve idle performance.	Assembly of test equipment is in progress.	75K FY 75 73K FY 76
Influence of Intensity and Scale of Turbulence on Emission Concentrations in the Primary Zone of a Gas Turbine Combustor/NASA Lewis	Prof. A.A. Kovitz at Northwestern University	To determine the effect of turbulence on emission concentrations within a premixed combustor using gaseous propane as a fuel.	Project has been completed and a technical report has been prepared.	48K/year FY 72, 73, 74

Table A-5

Government Sponsored Combustor Development Programs

NASA/Air Force

Program	Investigator	Objective	Status	Funding
Evaluation of Techniques for Pollution Reduction	NASA Lewis Research Center	Reduce emissions from turbojet combustors and reheat burners.	Continuing "in-house" effort. The effect of exhaust gas recirculation was examined and a final report is in preparation. Study of catalytic combustors was studied and the report issued. Altitude emissions of refanned JT8D was studied and the report issued.	250K FY 73 195K FY 74 50K FY 75 100K FY 76
In-house Exhaust Emissions Investigation	AFAPL	Provide limited investigated to further understanding of aircraft engine exhaust problems.	Program began April 1975 and will continue for 3 years.	Unknown
Swirl Can Combustors	NASA Lewis Research Center	Develop short-length high performance turbojet engine combustors having low levels of exhaust emissions suitable for Mach 3 flight.	Continuing "in-house" effort.	185K FY 73 125K FY 74 40K FY 75
Twin-Ram Induction Combustors	NASA Lewis Research Center	Develop a short double-annular combustors for advanced turbojet engines.	Task completed FY 74. Reports on final stage is complete.	50K FY 74
Basic Pollution Research	NASA Langley Research Center	a) Study reaction kinetics of NO formation in fuel rich systems behind shock waves. b) Study effort of very high pressure on NOx formation. c) Study the kinetics of soot formation and decay using laser light-scattering techniques. d) NOx formation studies in a jet-stirred reactor.	Continuing "in-house" effort.	50K FY 73 23K FY 74 60K FY 75
Single Combustor Rig Investigation of Turbine Engine Exhaust Emissions	AFAPL	To investigate novel control and measurement techniques.	Continuing "in-house" effort.	Unknown
Gas Turbine Catalytic Combustor	AFAPL & Engelhard Industries	Investigate the catalytic combustor concept.	Continuing "in-house" effort.	Unknown
Premixed Variable Geometry Combustors	NASA Lewis Research Center	Investigate the pollutant reductions possible with premixed, variable geometry combustors.	Project Completed.	125K FY 74
Multiple Point Fuel Distribution	NASA Lewis Research Center	Study ways of dividing and simultaneously regulating one flow stream into several equal flow multiple streams.	Project Completed.	150K FY 73

Table A-6

Government Sponsored Combustor Modeling Programs

Private Industry

Program	Investigator	Objective	Status	Funding
Combustors Design Criteria Validation/AMRDL	Garrett AiResearch	Develop and validate existing analytical combustor design procedures which can be used to significantly shorten the design time of 2-5 lb/sec. combustors.	Preliminary version of computer program is operational.	
Development of a 3-D Combustor Flow Analysis/AFAPL/FAA	United Technologies Research Center	To modify and extend an existing three-dimensional Navier-stokes calculation procedure which includes the effects of chemical reaction, turbulence transport, radiation energy flux, and droplet burning, and vaporization.	Program completed.	25K FY 74 91K FY 75
Low Power Turbopropulsion Combustor Emissions/AFAPL	Pratt & Whitney Aircraft	To identify and develop improved component design techniques which will increase part-power performance.	Project completed.	100K FY 71 600K FY 72 315K FY 73 178K FY 74
Combustor Flow Analysis Procedure AFAPL/FAA	United Aircraft Research Laboratory	To refine an existing analytical technique and develop a computational procedure for predicting combustion system performance.	Project completed.	85.8K FY 72
Analysis and Investigation of Exhaust Emissions from Non-Afterburning Aircraft Gas Turbine Engines During High Power/AFAPL	Pratt & Whitney Aircraft	Optimize design features through insight gained from analytical modeling of the combustor at low power and from experimental results.	Project completed.	75K FY 73 25K FY 74
Turbojet Combustor Pollution Formation/NASA Lewis	General Applied Science Laboratory	Develop a modular computer program to describe the coupled flow and combustion kinetics in a turbojet combustor.	Project completed.	50K FY 72 20K FY 73
Analysis of Combustion Systems with Swirl/NASA Lewis	Advanced Technical Laboratory	Perform numerical modeling of swirling flows using finite difference techniques for predicting the effect of swirl on combustor performance and emissions.	Project completed.	84K FY 71-73

Table A-7

Government Sponsored Combustor Modeling Programs

University Grants

Program	Investigator	Objective	Status	Funding
Study of Air Pollution from Aircraft/NASA Lewis	John B. Heywood at MIT	To predict NOx and CO levels in combustors and to investigate fuel atomization, fuel vaporization, and the mixing process inside the combustor.	Continuing research effort.	66K FY 74 79K FY 75 115K FY 76
Study of Parameters Affecting Emissions of Gas-Turbine Engines/NASA Lewis	Prof. C.W. Kauffman University of Cincinnati	Analyze combustor emission data and formulate a mathematical expression that correlates measured emissions with primary operating conditions.	Data in process of being analyzed.	33K FY 75-76
Basic Chemistry of Aircraft Pollutants/NASA Lewis	Professor A. Berlad SUNY-Stonybrook	Survey current reaction rate literature on chemical reaction affecting atmospheric ozone levels, establish analytical model of ozone balance in the atmosphere, and indicate required experimental rate data needed to solve model.	Project completed.	48K FY 73-75
Semi-Empirical Correlations for Aircraft Emissions/EPA	Prof. A.M. Mellor Purdue University	To determine a scaling theory for the prediction and optimization of pollutants for aircraft gas turbine combustors	Continuing research effort.	33K FY 72 40K FY 73 46K FY 74 60K FY 75 55K FY 76

Table A-8

Government Sponsored Combustor Modeling Programs

NASA/Air Force

Program	Investigator	Objective	Status	Funding
Turbine Engine Exhaust Emissions Technology	AFAPL	Develop ambient temperature and humidity correction factors for CO and HC.	Project completed.	40K FY 72-73
Aircraft Engine Emissions Correlation Technique	Air Force Weapons Laboratory	To predict CO, HC, and NOx and particulate emissions indicies for turbine engines used by the Air Force.	Continuing "in-house" effort.	2K FY 74-75 5K FY 76
Three Dimensional Combustion Flow Analysis	Wright-Patterson AFB	Develop a mathematical model of the combustion process for annular and can-annular combustors.	Project completed.	80K FY 72-74
Combustor Analytical Modeling of Pollution Formation	NASA Lewis Research Center	To study the effects of mixing and fuel preparation on the formation of emissions.	Project completed.	50K FY 74

Appendix B

Data Bank

The appendix summarizes the pertinent technical data for the combustor operating conditions and combustor emissions performance at various power levels for each production or baseline engine and various advanced emissions control concepts applied to that engine. For the advanced concepts, the best demonstrated concept of each complexity category (see Section II, Table III-1) is listed and its data tabulated. Data may come from actual engine test, engine rig test (raw or extrapolated data), or projection from related rig test. In addition, engine data was sometimes given only in terms of EPAP, thereby forcing an estimate of the associated EIs to be made. Consequently it must be recognized that not all of the data recorded herein are equally accurate or valid although considerable effort was made to cull the wheat from the chaff.

ENGINE: TFE 731-2

S/V = 9.92 ft^{-1} **T rated:** 3500 lbs. **IDLE POWER:** 5.7 **% rated**

PRODUCTION π_c: 13

	P_3	T_3	$\dot{M}_a$			$\dot{M}_f$						EI			
MODE	(atm)	(^oR)	(#/S)	Ω	f/a	(#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	1.87	640	4.61	.646	.0098	181					.035	22.4	61.4	3.0	
APPROACH	4.85	867	12.0	.199	.0120	521					.006	2.9	18.3	6.9	
CLIMBOUT	11.9	1147	26.2	.051	.0148	1385					.0003	.09	1.3	17.1	
TAKEOFF	13.0	1180	28.2	.044	.0155	1552					.0003	.09	1.2	19.2	
ADVANCED:	Air-assist fuel nozzle (Category = 1) (270 psig)														
IDLE											.0047	0.7	17.5	3.9	
		Same										Same			
APPROACH		as													
CLIMBOUT												as			
TAKEOFF		production													
ADVANCED:	Piloted airblast (Category = 2) Mod 1 - NASA (with air-assist at idle and approach)										production.				
IDLE			Same								.0127	2.5	45.1	2.97	
APPROACH			as								.0010	.15	3.9	6.1	
CLIMBOUT			Production.								.0005	.18	1.3	18.0	
TAKEOFF											.0003	.04	1.3	20.2	

ENGINE: TFE 731-2

S/V = 9.92 ft.$^{-1}$ T rated: 3500 lbs. IDLE POWER: 5.7 % rated

π_c: 13

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PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	1.87	640	4.61	.646	.0098						.035	22.4	61.4	3.0	
APPROACH	4.85	867	12.0	.199	.0120						.006	2.9	18.3	6.9	
CLIMBOUT	11.9	1147	26.2	.051	.0148						.0003	.09	1.3	17.1	
TAKEOFF	13.0	1180	28.2	.044	.0155						.0003	.09	1.2	19.2	
ADVANCED:															
	Premix/prevaporized combustor (Category 3-4)														
IDLE											.009	2.07	30.74		
		same													
APPROACH		as													
CLIMBOUT		production													
TAKEOFF															
ADVANCED:														3.77	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: ATF3

S/V = **T rated:** 4,050 **IDLE POWER:** **% rated**

PRODUCTION π_c**:** 23.0

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF	23.0		40.0			1820									
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT15D

S/V = 11.4 ft^{-1} | **T rated:** 2500 lbs | **IDLE POWER:** 8 % rated

π_c: 10.1

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	CO	NO_x
IDLE	1.82	659.11	5.49	1.0412	.0099	215					.0515	34.8	90.5	2.5
APPROACH	4.51	905.9	11.10	.2543	.0125	481					.0084	3.3	23.8	5.1
CLIMBOUT	9.31	1118.1	20.58	.0849	.0174	1247					.0003	0	1	9.1
TAKEOFF	10.12	1147.3	22.23	.0740	.0182	1405					.0002	0	1.0	10.1
ADVANCED:**	10% comp. bleed at idle and approach				(category = 1)									
IDLE	2.1	70	5.73	.7490	.0123	253					.0260	12.2	65.9	3.1
APPROACH	4.5	906	12.21	.2897	.0132	581						1.1	17.2	6.2
CLIMBOUT														
TAKEOFF			same as production.											
ADVANCED:	Airflow distribution/Injector modification							(Category = 2)						
IDLE			same								.0063	0.4	25.8	3.1
			as											
APPROACH											.0015	0	6.4	5.8
CLIMBOUT			production.								.0006	0	2.6	7
TAKEOFF											.0005	0	2.2	9.8

**HC and CO EIs estimated.

ENGINE: CJ610-2C

S/V = 8.51 ft.$^{-1}$ T rated: 2950 lbs. **IDLE POWER:** 6.64 **% rated**

π_c: 6.8

PRODUCTION

													EI		
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE		Engine data essentially the same as the CF700 data.				510					.052	18.0	1550	0.9	
APPROACH						1025					.023	2.7	88.0	1.5	
CLIMBOUT						2430					.006	0.2	27.0	3.7	
TAKEOFF						2780					.006	0.1	27.0	4.2	
ADVANCED:	Reduced spray cone angle (Category = 1)														
IDLE											.039	3.0	155	0.9	
APPROACH											.020	.6	85.6	1.5	
CLIMBOUT											.006	.1	27.0	3.7	
TAKEOFF											.006	.1	27.0	4.2	
ADVANCED:	Air flow distribution (Category = 2)														
IDLE											.004	14.7	134.9	0.9	
APPROACH											.020	2.9	74.3	1.5	
CLIMBOUT											.006	0.2	27.0	3.7	
TAKEOFF											.006	0.1	27.0	4.2	

ENGINE: CF700-2D

S/V = 8.51 ft^{-1} T rated: 4250 lbs IDLE POWER: 6.24 % rated

π_c: 6.6

PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hour)					$1-\eta_c$	HC	CO	NO_x	
IDLE	1.50	605	10.6	2.745	.012	460					.052	18.0	155.0	.90	
APPROACH	2.72	716	18.6	1.344	.014	919					.016	1.4	62.0	1.8	
CLIMBOUT	5.78	890	38.4	.518	.017	2322					.0059	0.1	25.0	4.3	
TAKEOFF	6.94	980	41	.337	.018	2607					.0052	0.1	22.0	5.6	
ADVANCED:	Reduced spray cone angle (Category = 1)														
IDLE			Same								.039	3.0	155.0	.90	
APPROACH			as								.0145	.57	60.3	1.8	
CLIMBOUT											.0059	0.1	25.0	4.3	
TAKEOFF			Production								.0052	0.1	22.0	5.6	
ADVANCED:	Airflow distribution (Category = 2)														
IDLE			Same								.044	14.7	134.9	.9	
APPROACH			as								.013	1.5	51.0	1.8	
CLIMBOUT			production.								.006	0.1	25.0	4.3	
TAKEOFF											.005	0.1	22.0	5.6	

ENGINE: M45H

S/V = T rated: 7500 lbs IDLE POWER: 5 % rated

PRODUCTION * π_c: 16

MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	EI CO	EI NO_x	
IDLE				3.4							.090	81.6	80		
APPROACH				1.0							.019	11.0	40.5		
CLIMBOUT				0.22							.0029	1.0	8.5		
TAKEOFF				0.20		3450					.0026	0.9	8.0		
ADVANCED:**															
	Unknown		(Category = 1-2)												
IDLE											.0088	2.56	28.2		
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

* Not yet in production

** HC and CO EIs estimated

ENGINE: RB401

S/V =

PRODUCTION *

T rated: 5000 lbs.

π_c: 17.0

IDLE POWER:

% rated

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF	17.0														
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

* Not yet in production

ENGINE: ALF502D

S/V = 11.76 ft.$^{-1}$ T rated: 6500 lbs. IDLE POWER: 6.2 % rated

PRODUCTION * π_c: 10.7

	P_3	T_3	$\dot{M}_a$			$\dot{M}_f$						EI			
MODE	(atm)	(^oR)	(#/S)	Ω	f/a	(#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	2.3	695	9.6		.0111	377					.0360	14.2	100.8	2.5	
APPROACH	5.2	900	19.8		.0117	844						-	-	5.0	
CLIMBOUT	10.3	1110	33.3		.0217	2456						-	-	13.0	
TAKEOFF	10.7	1125	34.5		.0240	2720						-	-	13.2	
ADVANCED:**	Air blast nozzle (no linear change) (Category 1)														
IDLE											.0206	9.9	51.3	4.4	
APPROACH												same as production			
CLIMBOUT															
TAKEOFF															
ADVANCED:	Airblast (Catecory 2)														
IDLE											.0142	5.3	41.1	2.8	
APPROACH												0.4	9.2	5.6	
CLIMBOUT												0.1	0.4	8.0	
TAKEOFF												0	0	8.4	

* Not yet in production

** HC and CO EIs estimated

ENGINE: CF6-6D

S/V = 7.56 ft^{-1}

PRODUCTION

T rated: 38900 lbs

π_c: 24.7

IDLE POWER: 3.34 % rated

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
												EI			
IDLE	2.73	783	22.3	.326	.0132	1063					.032	20.5	61.2	4.59	
APPROACH						3864					.0029	1.80	6.00	10.75	
CLIMBOUT						11329					.00066	.60	.60	27.29	
TAKEOFF	24.52	1403	156.6	.0140	.0244	13750					.00066	.60	.60	34.00	
ADVANCED:	Compressor Bleed			(Category = 1)											
IDLE						1290					.016	7.7	39.7	4.6	
APPROACH		same										same			
CLIMBOUT		as										as			
TAKEOFF		Production										Production			
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: CF6-50C

S/V = 8.28 ft^{-1} T rated: 49900 lbs IDLE POWER: 3.39 % rated

π_c: 29.8

PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	2.92	772	36.1	.576	.0098	1206					.043	30	73.0	2.5	
APPROACH	11.7	1134	125.0	.079	.0118	5280					.0010	0.01	4.3	10.0	
CLIMBOUT	25.9	1415	241.0	.022	.0181	15662					.0001	0.01	0.3	29.5	
TAKEOFF	29.8	1476	269.0	.017	.0195	18900					.0001	0.01	0.02	35.5	
ADVANCED:	Production combustor plus sector burning at idle (Category = 1)														
IDLE			same								.0105	2.2	36.0	3.6	**
APPROACH			as									same			
CLIMBOUT												as			
TAKEOFF			Production									Production			
ADVANCED:	Double annular combustor (fuel staging) (Category = 3)														
IDLE			same								.0064	2.2	19.3	3.0	
APPROACH			as								.0007	0	3.1	8.9	
CLIMBOUT											.0001	0	0.4	13.3	
TAKEOFF			Production								.0002	0.06	0.52	16.9	

** HC and CO EIs estimated

ENGINE: CFM 56

S/V = 10.68 ft^{-1} **T rated:** 22,000 lbs. **IDLE POWER:** 4 % rated

π_c: 24

PRODUCTION*

												EI		
MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	HC	CO	NO_x
IDLE											.0249	9.14	72.85	2.14
APPROACH											.0016	.29	5.71	7.3
CLIMBOUT											.0005	~ 0	2.29	16.1
TAKEOFF											.0005	~ 0	2.29	18.2
ADVANCED:**	Sector burning at idle (Category = 1)													
IDLE											.0175	5.0	56.5	4.4
APPROACH											same as Production			
CLIMBOUT														
TAKEOFF														
ADVANCED:	Airflow distribution with sector burning (Category = 2)													
IDLE											.0138	1.14	53.3	~ 4.4
APPROACH												~0	~0	~ 7.3
CLIMBOUT												~0	~0	~16.1
TAKEOFF												~0	~0	~18.2

* Engine not yet in production

**HC and CO EIs estimated

ENGINE: JT9D-7

S/V = 5.88 ft^{-1} **T rated:** 46150 lbs. **IDLE POWER:** 8.2 % rated

PRODUCTION π_c: 21.1

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					1-η_c	EI			
												HC	CO	NO_x	
IDLE	3.95	835	51.4	.226	.0100	1849					.044	29.8	77.0	3.1	
APPROACH	8.5	1055	99.4	.074	.0130	4648					.0031	1.0	9.6	7.8	
CLIMBOUT	18.5	1320	189.0	.021	.0194	13193					.0002	0.1	0.5	21.4	
TAKEOFF	21.1	1380	208.6	.017	.0215	16142					.0001	0.05	0.2	29.4	
ADVANCED:	Air assist (Category = 1)														
IDLE		same										7.0	45.7	3.1	
APPROACH		as													
CLIMBOUT													same		
TAKEOFF	Production												as		
													Production		
ADVANCED:	Aerating nozzle combustor (Category = 2)														
IDLE		same										1.1	6.9	2.9	
APPROACH		as												7.3	
CLIMBOUT														20.1	
TAKEOFF	Production													27.6	

ENGINE: JT9D-7 Continued

S/V = 5.88 ft.$^{-1}$ **T rated:** 46150 lbs. **IDLE POWER:** 8.2 **% rated**

π_c: 21.1

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr.)					$1-\eta_c$	EI HC	EI CO	EI NO_x	
IDLE	3.95	8.35	51.4	.226	.0100	1849					.044	29.8	77.0	3.1	
APPROACH	8.5	1055	99.4	.074	.0130	4648					.0031	1.0	9.6	7.8	
CLIMBOUT	18.5	1320	189.0	.021	.0194	13193					.0002	0.1	0.5	21.4	
TAKEOFF	21.1	1380	208.6	.017	.0215	16142					.0001	0.05	0.2	29.4	
ADVANCED:	Vorbix combustor (fuel staging) (Category # 3)														
IDLE											.0058	1.70	18.7		*
		Same													
APPROACH		as													
CLIMBOUT															
TAKEOFF		Production.													
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

* Estimated

ENGINE: JT9D-70

S/V = 7.14 ft^{-1} T rated: 51,150 IDLE POWER: 6.5% rated

π_c: 24.35

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)				$1-\eta_c$	EI HC	EI CO	EI NO_x	
IDLE	3.74	820	45.5		.011	1800				.01[illegible]	6.8	34.0	3.2	
APPROACH	9.66	1079	108.3		.015	5850				.0007	0.45	1.3	8.1	
CLIMBOUT	21.29	1357	211.4		.021	15980				.0002	0.15	0.3	24.2	
TAKEOFF	24.35	1414	234.1		.023	19380				.0002	0.15	0.2	31.0	
ADVANCED:	Air Assist Nozzle (Category 1)													
IDLE			same							.0063	1.3	22.3	3.4	
APPROACH			as								same			
CLIMBOUT											as			
TAKEOFF			production								production			
ADVANCED:	Aerating Nozzle Combustor (Category 2)													
IDLE			same							.0035	0.75	12.4	5.1	
APPROACH			as							.0008	0.31	2.2	8.0	
CLIMBOUT										.0003	0.20	0.45	17.5	
TAKEOFF			production							.0002	0.18	0.3	21.3	

ENGINE: JT9D-70 continued

S/V = 7.14 ft^{-1} T rated: 51,150 IDLE POWER: 6.5 % rated

π_c: 24.35

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	EI CO	EI NO_x	
IDLE	3.74	820	45.5		.011	1800					.0138	6.8	34.0	3.2	
APPROACH	9.66	1079	108.3		.015	5850					.0007	0.45	1.3	8.1	
CLIMBOUT	21.29	1357	211.4		.021	15980					.0002	0.15	0.3	24.2	
TAKEOFF	24.35	1414	234.1		.023	19380					.0002	0.15	0.2	31.0	
ADVANCED:	Staged Premix (Category 3) - Estimated														
IDLE		same									.0019	.73	5.6	3.5	
APPROACH		as									.0101	5.88	21.5	7.5	η ~ 98% at
CLIMBOUT											.0025	1.18	6.0	14.3	~ 60% power
TAKEOFF		production										0.20	0	16.1	~ 2+ % SFC Penalty
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT10D

S/V =

PRODUCTION

T rated: 22-24,000 lbs. **IDLE POWER:** % rated

π_c:

												EI			
MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT3D-7

S/V = 7.14 ft^{-1} T rated: 19000 lbs IDLE POWER: 5 % rated

PRODUCTION π_c: 13.5

													EI		
MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					1-η_c	HC	CO	NO_x	
IDLE	2.04	650	33.89	.5799	.0083	1013					.1399	123	139	2.2	
APPROACH	5.58	911	91.13	.1572	.0094	3084					.0064	2.1	19.5	5.3	
CLIMBOUT	11.84	1133	168.48	.0497	.0135	8188					.0008	0.4	1.9	9.6	
TAKEOFF	13.61	1185.8	186.86	.0389	.0148	9956					.0006	0.5	0.9	12.7	
ADVANCED:	Smokeless burner can, (Category = 2) Aerating nozzle														
IDLE		same									.0818	69.1	91.9	3.3	
APPROACH		as									.0034	0.5	12.8	8.0	
CLIMBOUT											.0003	0.1	1.1	14.4	
TAKEOFF		Production									.0002	0.1	0.5	19.1	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: JT8D-17

S/V = 7.69 ft^{-1} **T rated:** 16000 lbs **IDLE POWER:** 6.5 **% rated**

π_c: 17.0

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	EI			
												HC	CO	NO_x	
IDLE	2.45	708	26.8	.533	.0119	1150					.0156	8.78	34.0	3.4	
APPROACH	6.60	957	68.5	.144	.0114	2810					.0021	0.50	7.2	6.9	
CLIMBOUT	14.76	1212	133.2	.041	.0165	7910					.0003	0.05	1.0	15.6	
TAKEOFF	17.01	1281	146.0	.031	.0188	9980					.0002	0.05	0.7	20.3	
ADVANCED:	Air assist (Category = 1)														
IDLE		same									.0072	2.3	22.5		
APPROACH		as										0.5	7.2	6.9	
CLIMBOUT												0.05	1.0	15.6	
TAKEOFF	Production											0.05	0.7	20.3	
ADVANCED:	Aerating nozzle combustor (Category = 2)														
IDLE		same									.0046	1.93	12.7	2.8	
APPROACH		as									.0009	0.50	2.1	7.9	
CLIMBOUT											.0006	0.30	1.4	17.7	
TAKEOFF	Production										.0007	0.29	1.7	20.1	

ENGINE: JT8D-17 Continued

S/V = 7.69 ft.$^{-1}$ **T rated:** 16000 lbs. **IDLE POWER:** 6.5 **% rated**

PRODUCTION π_c: 17.0

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	EI CO	EI NO_x
IDLE	2.45	708	26.8	.533	.0119	1150					.0156	8.78	34.0	3.4
APPROACH	6.60	957	68.5	.144	.0114	2810					.0021	0.50	7.2	6.9
CLIMBOUT	14.76	1212	133.2	.041	.0165	7910					.0003	0.05	1.0	15.6
TAKEOFF	17.01	1281	146.0	.031	.0188	9980					.0002	0.05	0.7	20.3
ADVANCED:	Vorbix (fuel staging) (Category = 3)													
IDLE			same								.0049	.06	18.7	2.6
APPROACH			as										4.9	5.7
CLIMBOUT		production											7.8	9.1
TAKEOFF													6.8	11.5
ADVANCED:														
IDLE														
APPROACH														
CLIMBOUT														
TAKEOFF														

ENGINE: RB211-22B

S/V =

PRODUCTION

T rated: 42000 lbs

π_c: 25.0

IDLE POWER: 4.75% rated

MODE	P_3 (atm)	T_3 (°R)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	EI HC	 CO	 NO_x	
IDLE				1.4		1474					.106	92.9	106	2.2	
APPROACH						4499					.0118	7.8	21.4	6.5	
CLIMBOUT						12644					.0010	0.3	2.1	23.8	
TAKEOFF	25			0.1		15140						0.4	0.4	31.3	
ADVANCED:	Unknown (Category 1-2)														
IDLE											.0091	3.2	27.2	3.1	
APPROACH											.0010	0.4	2.8	9.8	
CLIMBOUT											.0005	0.2	1.3	28.5	
TAKEOFF											.0004	0.2	1.1	32.8	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: RB211-524

S/V = **T rated:** 50000 lbs. **IDLE POWER:** 6% rated

PRODUCTION π_c: 28

MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI			
												HC	CO	NO_x	
IDLE				0.33											
APPROACH															
CLIMBOUT															
TAKEOFF	28			0.043											
ADVANCED:	Unknown (Category = 1-2)														
IDLE											.0077	2.8	22.5	3.4	
APPROACH															
CLIMBOUT											.0008	0.3	2.3	10.6	
TAKEOFF											.0005	0.3	1.1	31.2	
ADVANCED:											.0004	0.2	1.0	36.2	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: Spey 511

S/V = **T rated:** 11400 lbs. **IDLE POWER:** 6 % rated

PRODUCTION π_c: 19.0

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)				$1-\eta_c$	EI			
											HC	CO	NO_x	
IDLE				0.68						.126	116	105.6		
APPROACH														
CLIMBOUT										.0064	2.1	19.7		
TAKEOFF						6950				.0007	0	2.7		
ADVANCED:	Unknown Category 1-2)									.0005	0	2		
IDLE										.0191	10.2	44.0	1.6	
APPROACH														
CLIMBOUT										.0086	4.5	20.0	9.9	
TAKEOFF										.0030	2.3	4.1	18.0	
ADVANCED:										.0005	0	2.3	20.1	
IDLE														
APPROACH														
CLIMBOUT														
TAKEOFF														

ENGINE: Spey 555

S/V =

T rated: 9850 lbs

IDLE POWER: 6% rated

PRODUCTION

π_c:

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	EI			
												HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:	Unknown (Category 1-2)														
IDLE						755					.0223	12.6	48.7	1.1	
APPROACH						1655					.0102	5.0	25.2	4.2	
CLIMBOUT						4501					.0052	3.6	8.6	11.2	
TAKEOFF						5516					.0036	2.7	5.1	14.9	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: Dart RDa7

S/V =

T rated: 2280 shp

π_c:5.75

IDLE POWER:

% rated

PRODUCTION

MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	EI CO	EI NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF	5.75					1530									
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: Tyne

S/V =

PRODUCTION

T rated: 5500 shp

π_c: 13.5

IDLE POWER:

% rated

	P_3	T_3	$\dot{M}_a$			$\dot{M}_f$						EI			
MODE	(atm)	(^oR)	(#/S)	Ω	f/a	(#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF	13.5					2475									
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: TPE 331-2

S/V = 15.18 ft^{-1} T rated: 715 shp IDLE POWER: 5 % rated

PRODUCTION π_c: 8.5

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	EI HC	 CO	 NO_x	
IDLE	2.70	770	2.43	.369	.0120	105					.0947	91.24	64.13	2.58	
APPROACH	7.21	1050	6.05	.093	.0101	220					.0062	2.67	16.61	8.29	
CLIMBOUT	7.98	1066	5.97	.074	.0173	372					.0007	.41	1.36	9.93	
TAKEOFF	8.13	1070	5.68	.068	.0198	405					.0006	.39	.95	10.23	
ADVANCED:	Primary only at taxi idle. (Category = 1)														
IDLE	2.79	769	2.69	.385	.0099	96					.0099	5.41	22.20	4.41	
APPROACH	7.10	1043	6.04	.097	.0103	224					.0066	3.25	16.15	8.80	
CLIMBOUT	7.94	1054	5.82	.075	.0180	377					.0005	.14	1.58	9.79	
TAKEOFF	8.01	1060	5.88	.074	.0194	411					.0004	.13	1.01	10.24	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: TPE 331-3

S/V = 15.18 ft^{-1} **T rated:** 840 shp **IDLE POWER:** 5 % rated

π_c: 10.4

PRODUCTION

	P_3	T_3	M_a			M_f							EI		
MODE	(atm)	(^oR)	(#/S)	Ω	f/a	(#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	3.07	793	2.61	.301	.0119	112					.084	79.11	61.53	2.87	
APPROACH	9.11	1122	7.31	.065	.0095	250					.002	.62	6.94	9.90	
CLIMBOUT	9.99	1142	7.15	.052	.0159	409					.0004	.14	.97	11.85	
TAKEOFF	10.09	1145	7.62	.054	.0167	458					.0003	.10	.77	12.36	
ADVANCED:	Primary fuel nozzles only at taxi idle (Category = 1)														
IDLE	3.07	792	2.50	.418	.0109	98					.0101	6.20	19.97	4.41	
APPROACH	8.84	1124	7.67	.071	.0096	265					.0014	.21	5.06	11.09	
CLIMBOUT	9.67	1142	7.15	.055	.0172	443					.0003	.18	.65	13.16	
TAKEOFF	9.74	1145	7.15	.054	.0179	461					.0004	.29	.63	13.36	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: T5321A

S/V =

PRODUCTION

T rated: 1,800 eshp

π_c: 8.0

IDLE POWER: 7 % rated

												EI			
MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	2.6	758	6.0		.0130										
APPROACH	4.81	895	9.2		.0148										
CLIMBOUT	7.75	1072	13.9		.0207										
TAKEOFF	8	1100	14.1		.0217	1026									
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: T53-L-13A

S/V =

PRODUCTION

T rated: 1400 shp

π_c:

IDLE POWER: 7 % rated

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	EI CO	EI NO_x	
IDLE	2.38	733	4.7		.0130	220					.0162	9.52	33.94	2.71	
APPROACH	4.39	868	7.2		.0148	380					.0017	0.39	5.97	4.78	
CLIMBOUT	7.07	1040	10.8		.0207	775						–	0.97	7.58	
TAKEOFF	7.3	1066	11.0		.0217	800						–	0.84	8.23	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: LTP101

S/V = 15.00 ft^{-1} **T rated:** 620 eshp **IDLE POWER:** 4.6 **% rated**

π_c: 8.4

PRODUCTION

	P_3	T_3	$\dot{M}_a$			$\dot{M}_f$						EI			
MODE	(atm)	(^oR)	(#/S)	Ω	f/a	(#/hr)					1-η_c	HC	CO	NO_x	
IDLE	3.33	830	2.32		.0115	67					.030	19.2	45		
2X IDLE	4.01	910	2.78		.0114										
APPROACH	5.03	935	3.26		.0133	172									
CLIMBOUT	8.0	1059	4.64		.0185	307									
TAKEOFF	8.3	1078	4.78		.0195	340									
ADVANCED:	Injector modification (Category = 1)														
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:	Airflow distribution (Category = 2)														
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: A11 250B15B

S/V = 9.76 ft^{-1} T rated: 400 shp IDLE POWER: 10 % rated

π_c: 7.2

PRODUCTION

												EI			
MODE	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	2.79	745	1.55	.485	.0112	63					.0403	20.18	97.35	1.45	
APPROACH	4.33	850	2.27	.265	.0142	85					.0158	5.18	48.6	2.18	
CLIMBOUT	6.83	1010	3.26	.125	.0207	245					.0024	0.38	9.0	5.95	
TAKEOFF	7.14	1030	3.35	.114	.0220	265					.0020	0.25	7.83	6.59	
ADVANCED:	Prechamber combustor; S/V = 9.11 ft^{-1} (category= 2)														
IDLE				.346							.0050	2.00	14.01	1.58	
APPROACH				.189							.0018	0.23	7.0	3.40	
CLIMBOUT				.089							.0018	0.060	7.4	5.52	
TAKEOFF				.081							.0014	.0436	5.76	5.81	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: A11 501D22A

S/V = **T rated:** 4400 shp **IDLE POWER:** 5 **% rated**

π_c**:** 9.7

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a	M_f (#/hr)					$1-\eta_c$	EI		
												HC	CO	NO_x
IDLE	3.64	795	15.0		.0113	610					.026	17.6	43.6	3.53
APPROACH	8.30	1059	33.0		.0096	1140					.0029	1.96	5.10	7.49
CLIMBOUT	9.45	1091	33.0		.0185	2198					.0013	0.89	2.06	9.22
TAKEOFF	9.70	1099	33.0		.0200	2376					.0007	0.28	2.04	8.88
ADVANCED:	Reverse flow combustor (Category = 2)													
IDLE			same								.0014	0.2	5.1	3.9
APPROACH			as								.0009	0.3	2.6	5.8
CLIMBOUT											.0004	0.2	1.1	10.8
TAKEOFF			production								.0003	0.1	1.1	11.0
ADVANCED:	Fuel staging (Category = 3)													
IDLE			same								.0017	0.36	5.85	5.15
APPROACH			as								.0009	0.58	1.67	6.88
CLIMBOUT											.0013	0.40	4.26	6.48
TAKEOFF			production								.0005	0.21	1.49	7.35

ENGINE: PT6A-27

S/V = 12.35 ft.$^{-1}$ T rated: 680 shp IDLE POWER: 3.37 **% rated**

π_c: 6.5

PRODUCTION

MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC*	 CO*	 NO_x*	
IDLE	1.90	6.93	2.5		.0107	115					.059	50.2	64.0	2.4	
APPROACH	4.15	906	5.0		.0112	215					.0007	2.2	23.0	4.9	
CLIMBOUT	6.24	1010	5.9		.0183	400					.0003	0	1.2	7.0	
TAKEOFF	6.48	1023	6.1		.0189	425					.0002	0	1.0	7.8	
ADVANCED:	Improved Primary Zone Mixing. Delayed quench (Category 2)														
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

*EPAPS calculated from this data do not agree with those from GAMA (Ref. 32) which are quoted in Table III-1. The EIs above were taken from Reference 20.

ENGINE: PT6A-41

S/V = 10.75 ft^{-1} **T rated:** 900 eshp **IDLE POWER:** 3 **% rated**

PRODUCTION π_c**:** 8.0

												EI			
MODE	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
IDLE	2.00	628	3.53	1.22	.0116	147					.12	101.6	115.3	1.98	
APPROACH	4.89	837	6.39	0.30	.0118	273					.029	22.7	34.8	4.65	
CLIMBOUT	7.76	982	8.22	0.13	.0161	473					.003	2.02	6.5	7.56	
TAKEOFF	8.12	1001	8.49	0.12	.0168	510					.0028	1.75	5.1	7.98	
ADVANCED:	Airflow distribution (Category = 2)														
IDLE	2.11	689	3.50	0.98	.0107	134					.0059	1.78	18.65	3.73	
APPROACH	3.71	845	5.15	0.39	.0101	188					.0016	.14	6.29	5.17	
CLIMBOUT	7.25	1077	7.32	0.11	.0161	424					.0004	.03	1.72	8.80	
TAKEOFF	7.52	1097	7.58	0.10	.0166	453					.0004	0.0	1.60	9.31	
ADVANCED:															
IDLE															
APPROACH															
CLIMBOUT															
TAKEOFF															

ENGINE: T-39

S/V =

PRODUCTION

T rated: 40 shp

π_c:

POWER	P_3 (atm)	T_3 (°R)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI			
												HC	CO	NO_x	
ADVANCED:															
ADVANCED:															

ENGINE: ST6

S/V =

PRODUCTION

T rated: 720 shp

π_c: 7.9

												EI			
POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	HC	CO	NO_x	
720 HP	7.9	1020	7.9			480									
ADVANCED:	Airflow distribution (Category = 2)														
ADVANCED:															

ENGINE: TSCP700-4

S/V = 8.25 ft^{-1}

PRODUCTION

T rated: 772 HP

π_c: 10.37

POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
639 HP	6.96	992	6.75	.058	.020						.0005	.183	1.550	7.108	
704 HP	7.16	1001	7.00	.056	.020						.0006	.244	1.446	7.377	
772 HP	7.77	1028	7.29	.048	.020						.0005	.189	1.328	7.806	
ADVANCED:	Water injection. (Category = 2)														
Rig	9.00	1105	9.71	.043	.016						.0002	.053	.737	12.04	
Rig	7.63	1110	8.00	.047	.018						.0002	.049	.540	11.93	
ADVANCED:															

ENGINE: GTCP660-4

$S/V = 9.50\ ft^{-1}$ T rated: 1100 HP

π_c: 3.5

PRODUCTION

POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI			
												HC	CO	NO_x	
958 HP	3.05	854	13.81	.430	.019	923					.0025	.224	9.608	4.924	
1045 HP	3.24	863	14.98	.428	.018	984					.0025	.400	8.972	5.119	
1141 HP	3.40	870	16.01	.403	.018	1024					.0022	.305	8.349	5.320	
ADVANCED:															
ADVANCED:															

ENGINE: GTCP30

S/V =

PRODUCTION

T rated: 78 HP

π_c: 3.76

POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a	$\dot{M}_f$ (#/hr)					$1-\eta_c$	EI HC	EI CO	EI NO_x	
	2.43	687	.947		.0198	67.5					.0014	.110	5.576	3.506	
	2.48	790	.963		.0199	69.0					.0014	.139	5.549	3.620	
78 HP	2.52	794	.954		.0201	69.0					.0013	.139	5.259	3.706	
ADVANCED:															
ADVANCED:															

ENGINE: GTCP 36-50

S/V =

T rated: 100 HP

π_c: 3.25

PRODUCTION

												EI			
POWER	P_3 (atm)	T_3 (^oR)	$\dot{M}_a$ (#/S)	Ω	f/a						$1-\eta_c$	HC	CO	NO_x	
79 HP	3.32	882	1.91		.017						.0057	.346	23.066	4.100	
94 HP	3.47	893	1.96		.018						.0043	.141	17.793	4.332	
103 HP	3.57	906	1.88		.020						.0028	.044	11.645	4.253	
ADVANCED:	Airblast (Category = 2)														
Rig		923	2.35		.0113						.0101	1.042	38.88	5.175	
Rig		926	1.77		.0207						.0018	.041	7.395	5.111	
ADVANCED:															

ENGINE: GTCP85-98

S/V = 8.70 ft^{-1} **T rated:** 293 HP

π_c: 3.36

PRODUCTION

Power	P_3 (atm)	T_3 (^oR)	M_a (#/S)	Ω	f/a						$1-\eta_c$	EI HC	 CO	 NO_x	
243 HP	3.30	863	3.97	.409	.019						.0023	.182	9.164	5.411	
277 HP	3.60	870	4.26	.370	.019						.0022	.163	8.87	5.593	
293 HP	3.74	876	4.36	.350	.019						.0020	.145	7.972	5.856	
ADVANCED:	Wide angle fuel Spray cone (Category = 1)														
160 HP	3.51	1000	4.21	.301	.0147						.0025	.173	9.809	5.73	
237 HP	3.29	990	3.79	.310	.0178						.0019	.077	7.876	5.780	
ADVANCED:															

Appendix C

Glossary of Emissions Control Concepts

1. Fuel Atomization - Pressure atomizer nozzle design changes can lead to changes in the character of the fuel droplet size distribution. This in turn affects the evaporation time and strongly influences the amount of HC left unburned. To a lesser extent, the change in the evaporation rates affect the local fuel-air mixture ratio and thus the local temperature which would likely affect the CO and NOx levels.

Decreasing the flow number (equal to the fuel flow rate divided by the square root of the injector pressure differential) reduces the droplet size and in turn the evaporation time. This results in a hotter local mixture which consumes the HC and CO. NOx, however, increases. This approach is not universally profitable, however, as experiments indicate that at low combustor inlet temperatures, no degree of atomization will improve the droplet evaporation as there is simply insufficient heat available.

Incorporation of this approach into a hardware system involves changing both the pressure differential across the injector and the orifice diameter as otherwise the fuel flow rate would be increased at each power setting because of the change in pressure. Changing the pressure differential requires only a new set of valves and possibly a pressure boost in the fuel pump.

2. Increase in Idle Speed - As engine power is reduced, HC and CO levels generally increase as a result of lower temperatures and pressures at the combustor inlet. By increasing the engine speed at idle, therefore, the levels of HC and CO should be reduced. However, the level of NOx may increase because of the increased temperature in the combustor. The increased idle speed is limited on turbofan and turbojet engines by the capability of the aircraft brake systems as there is an increase in thrust. This problem does not exist with turboprop (class P2) engines as the thrust can be held nearly constant by properly varying the propellor pitch with engine speed. Also, there is an attendant increase in fuel consumption and noise with increased engine speed.

3. Airbleed - The use of airbleed is merely a means of increasing the idle speed, particularly of a jet, without suffering the problems of increased thrust. The additional power is directed towards compressing and then dumping extra air instead of towards thrust. However, the use of airbleed results in increased fuel consumption which offsets some of the expected reductions in emissions (as with any increase in the idle speed).

4. Air assist - In the air-assist technique compressor air is diverted and compressed externally, and then discharged around the fuel injectors. This high velocity air is directed towards the fuel injectors to help break up the fuel droplets and thus eliminate locally rich hot spots. By eliminating the locally rich hot spots, NOx levels may be reduced. The high velocity airblast effect is maintained at all power levels especially at idle wherein the airblast technique (See 7) is ineffectual. This technique is therefore, very effective in reducing HC and CO emissions at low power and in low pressure ratio engines.

The results of experimental testing of combustors equipped with air-assist systems indicate that substantial reductions in low power levels of HC and CO emissions can be achieved with this technique. However, NOx appears to increase, apparently due to a higher flame temperature.

The use of air assist would have a large impact on aircraft hardware systems because of the requirement to redistribute and compress externally with an auxiliary compressor a part of the compressor air flow although its effect on the combustor itself is minimal.

5. Fuel Sectoring - Fuel sectoring is a method to improve the combustion conditions at idle and thereby improve HC and CO emissions. In essence it is like fuel staging in that fuel is selectively removed from part of the combustor and injected into another in order to achieve a desirable fuel/air ratio. Specifically, at idle when the combustor is burning quite lean and at a low flame temperature, the combustion efficiency is poor, resulting in much HC and CO, because of inadequate heat to vaporize the fuel and to stimulate the $CO \rightarrow CO_2$ reaction. This problem is resolved by cutting off the fuel entirely to part of the combustor (usually about half) and injecting it with the rest of the fuel into the remaining part of the combustor. This has two beneficial effects: (1) the flow number of the nozzle is necessarily reduced, improving atomization and (2) the fuel/air ratio is increased (richened) so that a hotter flame exists, improving vaporization of the fuel and enhancing the $CO \rightarrow CO_2$ reaction.

Hardware changes are minimal and involve only replacement of half the fuel nozzle valves with ones designed to open at a higher pressure. As such this control technique is particularly attractive for retrofit, especially in view of its nearly universal usefulness.

6. Nozzle Design - Pressure atomizer nozzle design changes intended to optimize the fuel spray cone angle, and thus the distribution of fuel in the primary zone, are relatively easy to incorporate into a combustor.

Decreasing the angle of a wide angle spray cone reduces wall wetting which in turn helps to reduce HC. Increasing the angle of a fuel rich narrow angle spray cone is also effective in reducing HC and CO levels since more complete combustion results from the better fuel distribution. An optimum angle must be found empirically.

There is no impact on the system hardware as only the fuel nozzle is changed and the new one is no more complex than the old.

7. Airblast - An alternative to the air-assist technique (See 4) is the airblast concept. This system is the same as the air-assist system except for the method used in creating the high velocity air around the fuel injectors. Here, the pressure differential that exists between the compressor and the combustor is employed to achieve high velocity air through a venturi system at the combustor inlet.

The basic concept is relatively simple since it requires only the addition of the venturi tubes. However, alone it usually improves the emissions only slightly. It proves to be necessary in most cases also to optimize the airflow distribution of the liner which is the reason this concept is placed in the second category of complexity.

Success in improving the combustion efficiency by utilizing this technique has varied among the manufacturers depending upon the extent to which the liner flow was optimized. Also, it may be expected that NOx will increase as a result of the better combustion efficiency. At low power especially in low pressure ratio engines, the pressure differential across the injectors is reduced causing the air velocity around the fuel injectors to be reduced. Therefore, the airblast effect on fuel atomization tends not to be as effective at low power where the bulk of the HC and CO is formed. The concept also tends to be less effective in reverse flow annular combustors as the nozzle is located so as not to be able to take advantage of the dynamic component of the pressure.

8. Increased Combustor Length - Increasing the combustor length increases the residence time of the reactants. This technique theoretically reduces the levels of CO and HC by allowing the reactions to proceed further toward the goal of CO_2 and H_2O. NOx, however, might increase for the same reason. Results of testing this combustor technique indicate that the CO and HC levels decreased as expected.

A consideration in using this technique is that the length of the combustor casing would be increased, a potentially major change in an engine which may be reflected as a change in the engine length and/or center of gravity, both of which would affect engine installation.

9. Water Injection - Water injected into the primary zone of the combustor results in a lower primary zone temperature. Test results with water injection indicate that the lower primary zone temperature in turn results in a reduction in NOx as a result of the lower $N_2 \rightarrow NO$ reaction rate. However, if the temperature is reduced too much, an increase in CO occurs.

The use of water injection presents a number of problems: (1) The increased aircraft weight due to the mass of water carried may reduce the useful payload of the aircraft. (Usually, however, water injection results in increased thrust, and hence the payload possibly can be increased); (2) Higher fuel consumption is required to maintain turbine inlet temperatures; (3) Precautions must be taken to prevent ice formation in the water injection system for operation at ambient temperatures below the freezing point of water; and (4) Water must be demineralized in order to prevent turbine blade corrosion and pitting. The use of tap water results in substantial turbine deterioration and thus compromises safety and engine reliability. Also, demineralized water can be very expensive (over $0.30 per gallon) depending upon the location. Logistics for demineralized water may be a problem also, especially for those aircraft using smaller fields.

10. Rich Primary - Theoretically, reducing the primary airflow increases the local fuel/air ratio and hence the primary zone temperature. At low power, this is beneficial in that the higher temperature enhances the $CO \rightarrow CO_2$ conversion when O_2 became available in the secondary and aids in fuel droplet evaporation, thereby improving the consumption of HC in the secondary. NOx may be expected to increase slightly. At high power, the rich primary is very hot, producing large quantitites of NOx. If the equivalence ratio is greater than one in the primary zone, smoke becomes a problem, requiring complicated air flow patterns in the secondary and dilution zones to consume it. Very limited results of testing this combustor concept verify the expected CO reductions and the ensuing smoke problem.

11. Lean Primary(1)*-There are two philosophies behind the lean primary depending upon the pollutant to be controlled. The first idea is not particularly difficult to implement and therefore it rates as a category 2 (modest complexity) scheme. The other concept rates as a category 2-3 scheme. If a primary zone is stoichiometric or rich (See 10), then there is possibly considerable CO emission because there is insufficient O_2 to complete the reaction to CO_2 ($CO + O_2 \rightarrow CO_2$). While this reaction can be completed further downstream when more air is added there is the danger that this air addition may either quench the reaction altogether or may occur too late for the reaction to go to completion prior to exhausting into the turbine wherein quenching will surely occur.

The solution here is to lean the primary sufficiently (ϕ, the equivalence ratio, is ≈ 0.9) so that there is adequate O_2 yet enough heat for the CO_2 reaction to occur at reasonable speed. This prevents the formation of large amounts of CO which must somehow be consumed later. Because of the availability of O_2 and the high temperature, any remaining HC can also be expected to be consumed. This would be most noticeable if the original primary had been extremely rich ($\phi \geq 1.5$).

12. Delayed Dilution - By delaying the introduction of dilution air, a longer combustion zone at intermediate temperatures is provided. This increases the residence time of the reactants which allows the CO to CO_2 conversion to approach equilibrium and for unburnt hydrocarbons to be consumed. The temperature in the intermediate zone should be, however, low enough so that NOx formation rates are slow. Very limited

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* Number refers to one of two different degrees of control generally recognized possible with this concept. Lean primary (2) is described is described in 14.

test data indicates that CO and HC are reduced, as anticipated, with only marginal increases in NOx. The difficulty lies in adjusting the air flow into the intermediate zone properly at all power settings so it is hot enough for CO consumption, yet cold enough to prevent NOx, and still achieving flame stability, liner durability, etc.

13. Premix (1)* - There are two philosophies behind the premix burner depending upon the pollutant to be controlled. The first approach is not difficult to develop into a combustor (geometry permitting) and therefore it rates as a category 2 (modest technology) concept; the other, while more effective against all pollutants, is quite complicated to handle and therefore rates a category 3-4 (See 16). The basic idea is that HC and CO emissions often arise because of poor mixing within the primary so that while the average equivalence ratio in the primary may be acceptable (slightly lean of stoichiometric in current practice), there are zones of excessively rich or lean mixture, both of which lead to HC and CO production. One way to prevent this is to premix (and prevaporize) the fuel prior to the flame zone so that the additional mixing time will lead to a more homogeneous mixture. In order to prevent flashback of the flame or deterioration burning, the premixing can be compromised a bit by keeping the local equivalence ratio above the stable deflagration limit in the premix zone. Upon entering the flame zone, further mixing can occur, permitting combustion. Although, this can lead to less than perfect mixing and thus reintroduce to a degree the original problem, the HC and CO emissions are much improved because of the partial mixing and total fuel evaporation in the premix zone.

NOx cannot be controlled by this approach unless total and lean premixing occurs which directly leads to the flashback problem, making premix for NOx control a category 3-4 scheme, as noted above. The excessively rich premix zone used here can lead to carbon deposition, however.

Implementation of this scheme into an existing design can be difficult in that the rather major combustor modifications must normally be kept within the constraints of the existing envelope. The more space that is taken for the premix region, the less that is available for dilution and pattern factor adjustments. Ideally, the combustor can be made longer with the premix zone merely being tacked onto the existing geometry (with some airflow adjustments).

14. Lean Primary (2)**-The lean primary zone is achieved by introducing a larger percentage of the total combustor airflow into the primary zone (where the fuel is injected). In sufficient amount, this creates a very lean, and therefore, cool flame which prevents the formation of NOx by lowering the $N_2 \rightarrow NO$ reaction rate. An emissions penalty is paid, however, through increased CO, a result of the lower temperature quenching the $CO \rightarrow CO_2$ reaction. This tradeoff has been witnessed in experiments. Used by itself, therefore, this concept is generally unacceptable. If CO can be controlled by some other combustor concept, then leaning the primary can be adapted for NOx reduction.

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* Number refers to one of two different degrees of control generally recognized possible with this concept. Premix (2) is described in 16.

**See also 11.

As with the premix concept discussed below (16), a very lean primary zone is subject to flame stability problems especially at low powers when the primary is at its leanest condition. Also, the larger amounts of airflow into the primary leave less air to be used further down the combustor for cooling the liner or adjusting the temperature profile into the turbine. This often leads to durability problems.

15. Fuel staging - The combustor is divided into two regions, each having its own fuel injection system. These are termed the pilot stage and the main stage. At low power, fuel is supplied only to the pilot stage, thereby allowing a much higher local fuel/air ratio that would be possible if the fuel were distributed throughout the combustor. This mixture is then able to burn hotter, enhancing the $CO \rightarrow CO_2$ conversion and droplet evaporation (aiding HC burning).

At high power, the fuel is distributed between the two stages in such a way so as to minimize the peak temperature. This aids in preventing NOx production. Generally, though, this type of combustor also incorporates air distribution features (See 10) or fuel preparation features (See 16) which further aids low NOx levels. Staging requires two fuel injection locations and adds to the complexity of the fuel supply system and the fuel control. The combustor liner is also more complex with additional cooling and temperature profile problems.

16. Premix (2)*- Fuel and air are mixed in a prechamber prior to entering the primary combustion zone. This premixing allows combustion to occur at a much leaner condition where NOx formation rates are slower. Experimental test results indicate that NOx reductions can be achieved where there is sufficient combustor inlet temperature to vaporize fuel droplets in the prechamber. This means that this technique is most applicable to high pressure ratio engines, which produce the required high combustor inlet temperatures.

With the premix concept careful attention must be given to the prechamber exit conditions. Exit velocities of the fuel-air mixture must be high enough at all power levels to prevent flashback which is very damaging to the liner and the nozzle. Also, in creating a lean primary zone combustor stability may be a problem leading to altitude flameout and difficulties in relighting.

The premix concept requires a significant change to the combustor liner geometry since the premix chamber must be included in the combustor. In some cases this has led unavoidably to a longer overall combustor and thus in the combuster outer casing.

17. Variable Geometry - Variable geometry provides control of the primary zone such that stable efficient combustion with minimum emissions occurs over the complete operating range of the engine. Air enters the combustor through holes equipped with a mechanism (usually a sliding ring) that meters the airflow in proportion to the fuel flow. With this system the primary zone fuel air ratio can be controlled to be stoichiometric at idle power for HC and CO reductions, and to be lean (but

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*See also 13.

stable) at high power for NOx reductions.

Very limited testing with this type of combustor has been conducted and therefore not much data are available. The data do indicate that HC and CO can be reduced with the variable geometry combustor. However, NOx improvements have not been significant, owing to inadequate design.

This system has a number of operational drawbacks, primarily the reliability of the mechanical system in such a severe environment which is a safety issue. However, the notion of moving mechanical systems in severe environments is not new to gas turbines: variable pitch compressor stators and variable turbine nozzle guide waves do exist.

18. Catalysis - Catalysis is a process by which a special substance, usually a solid substrate, causes the acceleration of a chemical reaction while not being permanently affected. Catalysis is often used on current automobiles to limit the emissions of HC and CO by the placement of the catalyst in the exhaust gas so that these pollutants, which are products of incomplete reaction in the cylinders, can be consumed.

In an aircraft engine, however, the catalyst would be placed in the combustor proper. This then permits the reaction to proceed under uniformly lean conditions, thereby giving a cooler flame and less NOx production while still consuming the HC and CO through the enhancement of the reaction rate.

Primary development problems are getting the catalyst to work quickly during the warm-up period, prevention of poisoning of the catalyst, prevention of mechanical wear on the catalyst material, prevention of excessive pressure loss through the catalyst bed, and prevention of flashbacks into the premixed air-fuel upstream of the catalyst.

Appendix D

DERIVATION OF THE NOx TECHNOLOGY CURVE (PRODUCTION ENGINES)

The curve through the data points in Figure 5 (production engine data) represents the level of technology achieved in current engines. The curve is established from the technology lines in Figures 22, 25, and 26 (the latter two being used to establish Figure 23) plus the following assumptions and observations:

1) Where known, the climbout contribution to the NOx EPAP is typically 56% of the total for T1 engines and 53% for T2 engines;

2) The climbout pressure ratio is roughly 92% of the rated pressure ratio for T1 engines and 87% for T2 engines; and

3) The climbout TSFC is assumed to be equal to the rated takeoff TSFC.

As an example, consider a 20,000 pound thrust engine (T2 class). First, from Figure 26, the rated pressure ratio is 23.0. The climbout pressure then is 20.01 (23.0 x .87), and the corresponding EI is 24.8 lb/1000 lb. fuel (Figure 25). The rated (=climbout) SFC from Figure 22 is .383 lbm/lbf-hr and hence the climbout (85% rated thrust) fuel flow is 6511 pounds per hour. For a 6% idle thrust, the impluse is 1776.7 lb-hrs. The climbout contribution to the EPAP is then (6511 x 24.8 x 2.2 ÷ 60) ÷ 1776.7 = 3.33. Total EPAP is 3.33 ÷ .53 = 6.28 for a 20,000 pound-thrust engine which falls right in the middle of the data. Actually this is to be expected as the scatter of engine data points about the mean curves on each of Figures 25, 25 and 22 is quite small. Figure 25, in particular, is a modified Lipfert curve which represents an excellent correlation. The rated TSFC variation shows excellent correlation except for the engines of older design.

Appendix E

NOx Calculations for Newly Certified T Class Engines

The data which forms the basis of this NOx projection comes from the CF6-50C engine employing the GE/NASA double annular combustor concept. Testing was done as a part of the NASA Experimental Clean Combustor Program. In order to extrapolate this data from the demonstration engine (CF6-50C) to the hypothetical engine, it is necessary to know first the operating conditions of the hypothetical engine and second a means of extrapolating. The extrapolation method is found in reference 59 wherein the double annular data is also found. The conversion formula offered is:

$$EI(NOx)_{NCE} = EI_{(NOx)_{CF6}} \left(\frac{P_{NCE}}{P_{CF6}}\right)^n \left(\frac{T_{exit,\ NCE}}{T_{exit,\ CF6}}\right) \exp\left(\frac{T_{inlet,\ NCE} - T_{inlet,\ CF6}}{288}\right)$$

($n = 0.2$ on approach and 0.5 elsewhere)

The operating conditions at partial power are estimated by ratioing down the known (postulated) conditions at full power according to ratios that exist in current engines. Specifically, given the rated pressure ratio (RPR) and the TIT (turbine inlet temperature), the following steps are taken:

(1) From the rated pressure ratio, T_{inlet} at takeoff is calculated ($\eta_c = 0.89$).

(2) With T_{exit} (TIT) specified and T_{inlet} known at full power, the rated SFC is calculated (Figure 45) and from the specified size of the engine, the fuel flow rate ($\dot{M}_f$) at full power is calculated.

(3) For the large engine at the other power modes, P, T_{inlet}, T_{exit}, and $\dot{M}_f$ are estimated by employing the partial power to full power ratios found on the JT9D-7, while for the small engine the same procedure is followed using the TFE 731 ratios.

For the two engines postulated, this procedure yields the operating conditions presented in Table E-1 in which the CF6-50C conditions and EI(NOx) are also listed. The above conversion formula then gives the EI(NOx) at each power and for each NCE: This is also listed in the table. As EPAP is computed by:

$$EPAP = \frac{\sum_{modes} EI \times \dot{M}_f}{\sum_{modes} Thrust \times time}$$

with units of the individual terms and magnitudes of the LTO cycle terms consistent with the requirements of reference 66, calculation may proceed directly.

Table E-1

Mode	Demonstration Engine (CF6) PR	CIT*	TIT	EI(NOx)	Large Engine $\dot{M}_f$	PR	CIT	TIT	EI(NOx)	Small Engine $\dot{M}_f$	PR	CIT	TIT	EI(NOx)
Idle	2.92	770	1550	3.0	1050	6	930	1510	5.7	140	3	745	1575	2.9
Approach	11.7	1130	2040	8.9	3360	16.1	1225	1940	10.8	440	7.5	955	2020	5.8
Climbout	25.9	1420	2710	13.3	9520	35.1	1530	2650	18.7	1170	18.3	1265	2580	7.9
Takeoff	29.8	1480	2860	16.9	11650	40	1600	2860	24.7	1310	20	1300	2680	9.3

*All temperatures are in degrees Rankine.

Appendix F

Newly Certified P2 Class Standards - Computation

In the computation of the technology lines for the emissions performance of newly certified P2 class engines, two engines are used, one, small (5000 horsepower), and the other, large (50,000 horsepower). The specifications of these engines are presented in Table III-7. In order to compute the emissions it is necessary to know both the emissions performance of the combustor and the fuel consumption at each of the four power modes of the landing-takeoff (LTO) cycle. Furthermore, to know the emissions performance, it is necessary to convert data from a known application (i.e., operating conditions) to the application in question. This means, of course, that it is necessary to know the operating conditions for both the initial application and the one under investigation (again, for each mode, as necessary).

50,000 horsepower engine

Table F-1 summarizes the operating conditions and engine performance of the large P2 engine under consideration. The takeoff (rated) pressure ratio (PR) and turbine inlet temperature (TIT) are hypothesized (Table III-6) and the air mass flow rate selected to supply the necessary total power output. The fuel flow rate is based then on the TIT requirement. For the intermediate powers, the pressure ratio is based upon scaling the intermediate power pressure ratios from known engines, and the combustor inlet temperature (CIT) is then determined by assuming an adiabatic efficiency of 0.85. The air flow rate is essentially constant for the flight modes as the compressor runs at a constant speed; at idle, the air flow rate is reduced. The fuel flow rate is selected to provide the necessary net power output specified by the mode (e.g., climbout is at 90% maximum rated power). The power specific fuel consumption (PSFC) is then calculated by conventional means.

5,000 horsepower engine

Table F-2 summarizes the operating conditions and performance of the small P2 engine (the lower limit). The takeoff (rated) pressure ratio and turbine inlet temperature are hypothesized (Table III-6), and the rated air flow rate selected to provide the necessary power, as before. The intermediate power point numbers are found in the same fashion as those for the large engine.

Emissions - HC, CO

The technology necessary for the control of HC and CO has already been demonstrated in several engines (JT9D-70, JT8D-17, TFE 731-2) and it forms the basis of the standards for the competing T2 class newly certified engines (Section III, part D). The technology lines are given

Table F-1

Large Advanced P2 Class Engine

Mode	PR	CIT (°F)	TIT (°F)	$\dot{M}_{air}$ (lbs/sec)	$\dot{M}_{fuel}$ (lbs/hr)	Power *(horsepower)	% rated	PSFC
Idle	15	1200	1780	105	3,280	3,000	6	1.09
Approach	34.2	1520	2220	235	9,070	15,000	30	0.60
Climbout	39	1580	2770	235	17,550	45,000	90	0.39
Takeoff	40	1600	2860	235	18,820	50,000	100	0.38

Table F-2

Small Advanced P2 Class Engine

Mode	PR	CIT (°R)	TIT (°R)	$\dot{M}_{air}$ (lbs/sec)	$\dot{M}_{fuel}$ (lbs/hr)	Power *(horsepower)	% rated	PSFC
Idle	7.5	970	1600	11.0	350	300	6	1.18
Approach	17.1	1240	1990	24.2	980	1500	30	0.65
Climbout	19.5	1290	2580	24.2	1890	4500	90	0.42
Takeoff	20	1300	2680	24.2	2030	5000	100	0.41

* After reduction gear losses

on Figures 50 and 51. This is achieved by the use of aerating (air-blast) or air-assist (external boost) nozzles with optimally adjusted liner airflow distribution. Emissions index (EI) data from those lines must be converted from the operating conditions of the demonstration engines to the conditions of the advanced P2 class engine in question (Tables F-1, F-2). Fortunately, only idle need be considered, for as reflected in equation (2) virtually all of the products of incomplete combustion (HC and CO) produced from a low emissions combustor over an LTO cycle will be produced at idle, the point of the most adverse conditions.

Table F-3 below summarizes the predicted emissions index performance of the two P2 class engines under investigation, as extracted from Figures 50 and 51 using the idle PR data in Tables F-1 and 2:

Table F-3

Large Engine:

P2 engine		
PR	EI(HC)	EI(CO)
15	0.2	11.8

Small Engine:

P2 engine		
PR	EI(HC)	EI(CO)
7.5	0.3	9.1

Emissions - NOx

The expected technology for NOx control comes from the application of such control techniques as staging, lean burning, and premix/prevaporization such as are being demonstrated in rig and engine tests as part of the present NASA Experimental Clean Combustor Program. Emissions index data for the most successful development so far, the double-annular staged burner (CF6-50 application) can be converted to reflect the operating conditions of the advanced P2 class engines under consideration here by the formula (reference 59):

$$\mathrm{EI\ (NOx)}_2 = \mathrm{EI\ (NOx)}_1 \left(\frac{P_2}{P_1}\right)^n \frac{\mathrm{TIT}_2}{\mathrm{TIT}_1} \exp\left[\frac{(\mathrm{CIT})_2 - (\mathrm{CIT})_1}{518}\right]$$

($n = 0.2$ on approach and 0.5 elsewhere).

Table F-4 shows the results of this conversion. Note that all modes must be considered unlike the case for the HC and CO emissions, for here the pollutant is produced in significant quantities in all modes.

Predicted Emissions Performance

It is now possible to calculate the emissions performance of the two hypothetical advanced P2 class engines. The emissions performance is measured here by the EPA parameter (EPAP), the parameter with which the EPA aircraft engine emissions standards are based (reference 66). (For the P2 class the units of the EPAP are pounds of pollutant per LTO cycle per 1000 horsepower x hours over the LTO cycle.) The formula is simply

$$\mathrm{EPAP} = \frac{\sum\limits_{\mathrm{modes}} \mathrm{EI} \times \dot{M}_f}{\sum\limits_{\mathrm{modes}} \mathrm{Power} \times \mathrm{time}}$$

with units of the individual terms consistent with the specified units of EPAP. The summation is over the four modes of the LTO cycle. The EIs are specified in Tables F-3 and F-4, the fuel flow rates and powers in Tables F-1 and F-2, and the times in mode in reference 66. For HC and CO, the EIs in the flight modes are assumed to be negligible. The results are, for the small engine,

EPAP (HC) = 0.1
EPAP (CO) = 2.9 (5000 horsepower)
EPAP (NOx) = 5.9 ,

and for the large engine,

EPAP (HC) = .1
EPAP (CO) = 3.6 (50,000 horsepower)
EPAP (NOx) = 13.4

From these points, the technology curves are generated. For the NOx

Table F-4

Mode	Demonstration Engine (CF6)				Large Engine				Small Engine			
	PR	CIT*	TIT	EI(NOx)	PR	CIT	TIT	EI(NOx)	PR	CIT	TIT	EI(NOx)
Idle	2.92	770	1550	3.0	15	1200	1780	17.6	7.5	970	1600	7.3
Approach	11.7	1130	2040	8.9	34.2	1520	2220	25.3	17.1	1240	1990	11.5
Climbout	25.9	1420	2710	13.3	39	1580	2770	23.1	19.5	1290	2580	8.7
Takeoff	29.8	1480	2860	16.9	40	1600	2860	24.7	20	1300	2680	9.3

*All temperatures are in degrees Rankine curve in particular (Figure 59), the EPAP is taken to be constant above 20,000 HP given the same PSFC characteristics. For such engines, NOx control techniques should be equally effective as surface to volume (S/V) effects do not substantially affect the NOx emissions index.

Appendix G

Calculation of NOx Trend Line for Category 3 Technology

In order to reasonably predict the performance of fuel staging in general terms for existing engine models (describing a trend line on Figure 33, EPAP (NOx) vs. thrust), it is necessary to be able to extrapolate the test data to expected values in the representative (or "trend") engine in question. To accomplish this extrapolation, the best presently known formula is given in reference 59:

$$\mathrm{EI(NOx)} = \mathrm{EI}_{\mathrm{ref}} \times \left(\frac{P}{P_{\mathrm{ref}}}\right)^{0.5} \times \left(\frac{\mathrm{TIT}}{\mathrm{TIT}_{\mathrm{ref}}}\right) \times \exp\left[\frac{\mathrm{CIT} - \mathrm{CIT}_{\mathrm{ref}}}{518}\right] \qquad (1)$$

where the subscript "ref" indicated the reference engine on which the testing was actually performed and

P = combustor pressure
TIT = turbine inlet temperature
CIT = combustor inlet temperature (compressor discharge pressure).

From Figure 40 it is determined that the NASA GE double annular combustor offers the greatest potential for NOx control of the three concept/engine combinations shown (conclusion based upon the fact that it has the lowest average slope, $\frac{\partial\ \mathrm{EI(NOx)}}{\partial\ \mathrm{(PR)}}$, over the pressure range tested). Other concepts were tested in each of these three engines in the course of the NASA study, but this graph presents only the best (selected for further development). The reference conditions then become for the takeoff condition of the CF6-50C (reference 59):

P_{ref} = 29.5 atm

$\mathrm{TIT}_{\mathrm{ref}}$ = 2855°R

$\mathrm{CIT}_{\mathrm{ref}}$ = 1475°R

$\mathrm{EI}_{\mathrm{ref}}$ = 16.9

The calculation proceeds as follows:

1. From Figures 28 and G-1, the rated pressure ratio (PR) and turbine inlet temperature (TIT) are found for the "trend line" engine at the rated thrust level in question.

2. The combustor inlet temperature (CIT) is calculated from:

$$\frac{\mathrm{CIT}}{T_\infty} = \left[(\mathrm{PR})^{\frac{\gamma-1}{\gamma}} - 1\right]\frac{1}{\eta_c} + 1 \qquad (2)$$

where T_∞ = 519°R and η_c is taken to be 0.89, a good average, especially for T2 class engines.

3. This data is then used in equation (1) to give the rated or takeoff EI(NOx) for that thrust engine using the double annular combustor.

4. For the other modes (idle, approach, climb-out), which must also enter into the calculation, the EIs are found by ratioing the rated EI(NOx) computed in step 3 according to the ratios experienced by the CF6-50C reference engine in its modes.

5. Determine the fuel flow rate ($\dot{M}_f$ = TSFC x thrust).

6. Estimate $\dot{M}_f$ at the other modes by ratioing the TSFC according to the average TSFC ratio of a cross section of production engines, specifically,

Mode	$\frac{\text{(TSFC) mode}}{\text{(TSFC) take off}}$ (T2)	$\frac{\text{(TSFC) mode}}{\text{(TSFC) take off}}$ (T1)
Takeoff	1.000	1.000
Climb-out	0.967	0.970
Idle	1.732	2.022

(Again, $\dot{M}_{f\ mode} = TSFC_{mode} \times thrust_{mode}$).

7. Calculate the EPAP by the formula,

$$EPAP(NOx) = \frac{\sum_{mode} EI(NOx) \times \dot{M}_f \times TIM}{\sum_{mode} (\text{thrust level}) \times TIM}$$

(TIM = time in mode)

For example, a 30,000 lb-thrust engine would have, by Figures 28 and G-1,

PR = 23.4 atm
TIT = 2750 °R

Equation (2) then gives CIT = 1380°R and Equation (1) gives EI(NOx) = 12.07 for takeoff. From reference 59 or Figure 40 the ratios of the partial power EIs to the takeoff EI for the CF6-50C these engine are,

Mode	$\frac{\text{EI (mode)}}{\text{EI (takeoff)}}$
Takeoff	1.000
Climbout	.787
Approach	.757
Idle	.178

Applying these ratios to the new 30,000 lb-thrust engine given,

Mode	EI(NOx)
Takeoff	12.07
Climbout	9.50
Approach	9.14
Idle	2.15

Equation (3) is then employed.to compute the EPAP. The particulars are presented in Table G-1. For T1 engines, the times in modes will differ, of course, according to the specifications in FR vol. 38, No. 136, pp. 19088.

Table G-1

Mode	t	$\dot{M}_f$	EI(NOx)	lbs NOx	% power	impulse
Idle	26	1155	2.15	1.08	6	780
Approach	4	3360	9.14	2.05	30	600
Climb-out	2.2	9120	9.50	3.18	85	935
Takeoff	0.7	11100	12.07	1.56	100	350
TOTAL				7.87		2665

$$\text{EPAP} = \frac{\Sigma \text{ lbs NOx}}{\left[\frac{\Sigma \text{ impulse}}{1000}\right]} = 2.95$$

TURBINE INLET TEMPERATURE
vs.
RATED PRESSURE RATIO
- PRODUCTION ENGINES

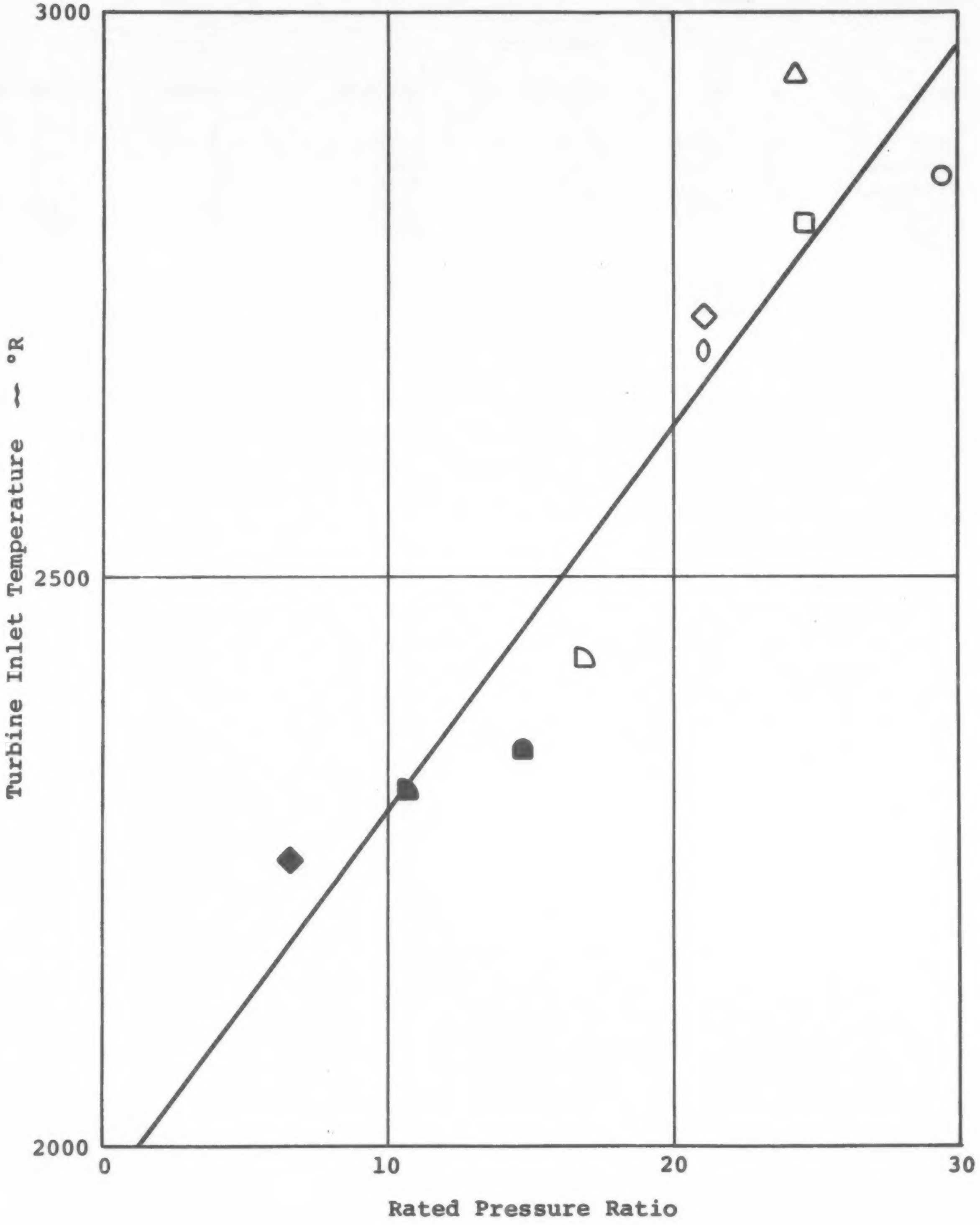

Figure G-1